Understanding the surface condition of gamma irradiated epoxy alumina nanocomposites adopting wavelets and fractal technique

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Abstract
The influence of alumina nanofiller and gamma irradiation on the surface potential variation of epoxy-alumina nanocomposites was investigated. The surface potential decay rate of nanocomposites has increased and the trap depth decreased with alumina nanoparticles addition to the matrix as well as upon exposure to gamma irradiation. Surface roughness was estimated using the wavelets and fractal technique. Daubechies wavelet of order 4 (db4) wavelet was chosen as the most suitable mother wavelet for surface roughness measurement. Multi resolution signal decomposition (MRSD) analysis of surface profile has revealed that with increasing wt% of alumina nanofiller in the nanocomposites, reduction in surface roughness of nanocomposites was observed. Upon gamma irradiation, the surface roughness factor at each level of MRSD has increased marginally. Fractal dimension and lacunarity were calculated for unaged and gamma ray irradiated samples and it exhibits inverse correlation.

1. Introduction
Epoxy resin are widely used as an insulant in power equipment operated in harsh environments, especially the space applications and in nuclear power plants, because of their superior dielectric properties [1, 2]. In recent times, epoxy nanocomposite materials are found to exhibit enhanced mechanical, thermal, and electrical properties [3–5]. The mechanical, microstructural, and thermal properties of nanocomposites can be achieved on addition of pyrolyzed carbon black nanofiller, pyrolyzed oil rubber, chicken feather fiber (CFF) and carbon residuum (CR) [6–8]. Gao et al have observed that electron beam irradiated epoxy/Al2O3 nanocomposites materials show high partial discharge resistance [9]. Surface charge accumulation is one of the major problems with the insulating material used in the power apparatus, which can initiate the surface discharge process to occur causing early failure of insulating material [10].

Multiple changes occur to the surface of the polymer insulating material, on irradiation of polymer material, which can cause characteristic variation in its fundamental insulation properties [11]. Murray et al studied the impact of gamma ray and electron beam irradiation on the mechanical, structural, and physico-chemical properties of the polymeric materials and observed that gamma irradiation has high impact on the surface roughness of the polymeric materials [12]. Hence, it is essential to understand the impact of dosage of gamma irradiation on the surface roughness of the epoxy nanocomposites.

Wavelet transform is considered to be one of the promising methods to analyse the surface morphology of the epoxy nanocomposites [13, 14]. Different morphological changes on the surface of epoxy nanocomposites can be understood using multiresolution signal decomposition (MRSD) technique at different analytical resolutions and decomposition level [15]. The fractal dimension and lacunarity also give the deep insight about the surface roughness of the materials [16]. Literature on the analysis of surface profile of epoxy nanocomposites and with gamma irradiated specimens adopting wavelet technique is also scanty.

Having known all these facts, an attempt has been made to understand the impact of gamma irradiation on surface characteristic variation of epoxy-alumina nanocomposites by adopting MRSD technique to surface
roughness profile and by analysis of surface charge accumulation studies. Also, the variation in the surface roughness characteristics of gamma irradiated epoxy alumina nanocomposites were analysed by measuring surface profile measurement and analysis was carried out through fractal dimension and lacunarity.

2. Experimental studies

2.1. Sample preparation
The alumina nanoparticles with size of 20–30 nm (procured from the Richem international, USA) were dried at 150 °C in order to remove the moisture in it. Figure 1 shows the schematic representation for the different steps involved in the fabrication of epoxy alumina nanocomposites. The dried alumina nanoparticles were mixed in ethanol and were kept for sonication for 1 h, operated at a frequency of 20 kHz. This sonication process ensures the proper dispersion of alumina nanoparticles in ethanol. Then the alumina-ethanol solution was mixed with the required quantity of epoxy resin (Araldite CY 205 IN Liquid, solvent-free, unmodified Bisphenol A epoxy resin procured from HUNTSMAN) and was shear mixed at a speed of 4000 rpm for 6 h. The shear mixing ensures the proper mixing of alumina nanoparticles and epoxy resins. After shear mixing, epoxy-alumina mixture were kept for sonication for 1 h at a frequency of 20 kHz, for the uniform dispersion of these alumina nanoparticles in the epoxy resins. Then the mixture was kept in hot air oven at 100 °C, to vapourise the ethanol. After this, hardener (tri-ethylene tetra-amine procured from HUNTSMAN), amount equivalent to the 11% of the quantity of pure epoxy was added to the alumina-epoxy mixture and was kept for degassing. The degassing removes bubbles from the mixture. Finally, alumina-epoxy-hardener mixture was casted in a mould and 0 wt%, 1 wt%, 3 wt%, and 5 wt% of alumina filled epoxy nanocomposites were fabricated. If any voids present in epoxy resin, under electrical stress can create internal damage to the insulating material due to partial discharges. The remnant charges after discharge gets distributed into the walls of the void, which can alter the local electric field [17]. Admittedly, further work need to be carried out by positioning the void of different size to understand the surface potential variation and trap depth variation, which will be taken as part of future work. The prepared nanocomposites were irradiated by 60Co gamma-rays in air ambience with a dosage rate of 660 Gy h\(^{-1}\) to total gamma irradiation level of 5 kGy, 10 kGy, and 15 kGy.

2.2. Surface potential measurement
Figure 2 shows the surface potential decay measurement setup. Function generator was used to generate dc voltage profile and a trek amplifier (Trek model 20/20C) was used to amplify the generated dc voltage. A needle electrode was used to inject the charge on the surface of the sample (at Position 1) by generating a corona discharge at ±10 kV DC voltage. After 5 min of charging, the sample was moved to Position 2 under the sensor to measure the surface potential variation. An electrostatic voltmeter monitored the surface potential decay which was continuously recorded in a digital storage oscilloscope (DSO).

2.3. Surface morphology measurement
Surface morphology of unaged and gamma irradiated nanocomposites were measured using a surface profilometer (Surface Profiler I Model: Veeco NT 1000 Veeco Instruments Inc., Thailand) in a vertical scanning interferometer (VSI) mode. The measurement was done at the magnification of 10.87 with scan area of 640 μm × 480 μm.
2.4. Wavelet transform and multi resolution signal decomposition

Wavelets technique is now well adapted to process the surface roughness signal and to decompose the signal at various analytical resolutions to get the intricate detail on surface morphology of the specimen [18]. The wavelet technique is applied by using a family of functions which are generated by the translations and dilations of the mother wavelet [14]. The mother wavelet with the dilation parameter $a$ and translation parameter $b$ can be represented as

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t - b}{a}\right), \quad a, b \in \mathbb{R}; \quad a \gg 0,$$

and the continuous wavelet transform (CWT) can be represented as

$$W_t(a, b) = \langle f, \psi_{a,b} \rangle = \frac{1}{\sqrt{a}} \int_{\mathbb{R}} f(t) \psi\left(\frac{t - b}{a}\right) dt,$$

If the dilation parameter $a$ and translation parameter $b$ chosen in the form $a = 2^{-j}$ and $b = k2^{-j}$, where $j, k \in \mathbb{Z}$, then discrete wavelet transform (DWT) can be written as

$$\psi_{j,k}(t) = \psi_{2^{-j},k2^{-j}}(t) = 2^{j/2} \psi(2t - k),$$

$$W_f(a, b) = \langle f, \psi_{j,k} \rangle = 2^{j/2} \int_{-\infty}^{+\infty} f(t) \psi(2t - k) dt,$$

MRSD can be used to decompose the signal at various levels of resolutions. In the present study, MRSD is applied to the surface profile signal. The MRSD process involves the decomposing the original signal $C^o$ using an orthogonal wavelet based filter into two frequency components i.e. the low frequency component $C^o_n$ and the high-frequency component $D^o_n$. Approximation information and detail information of the original can be acquired by the low frequency and high frequency components at the first scale of decomposition respectively. The low frequency component of the original $C^o$ again can be decomposed at the second scale into the low and high frequency components which can be further represented as $C^o_{n+1}$ and $D^o_{n+1}$ respectively. These decomposition processes can be further continued to get the desired signal. The maximum number of decomposition level ($d$) can be expressed as

$$d \leq \log_2 M,$$

where, $M$ is the number of sampling data points. Further these low frequency component and high frequency component obtained after different scale of decomposition can be expressed in terms of low pass filter $h$, and high pass filter $g$, as

$$C^i_n = \sum_{j=0}^{n} C^{i-1}_{j-n} h_{j-n},$$

$$D^i_n = \sum_{j=0}^{n} C^{i-1}_{j-n} g_{j-n},$$

where, $n$ is the sampling position and $i$ is the decomposition scale level.

In the present work, 1D and 2D MRSD analysis was performed on the surface roughness profile signal. Figure 3 shows the schematic diagram of the 2D MRSD process. $g$ and $h$ respectively represent the high pass filter and low pass filter. Low pass filters remove the high frequency fluctuations and provides the approximate information about the original signal ($C^o$), and output of this low pass filter gives the approximation coefficient. Similarly, high pass filters provide the detail information about the original signal ($C^o$) an output of it gives the
details coefficient. Thus, at first, original signal ($C^0$) is split into the translated and dilated version of the mother wavelet, as an approximation signal ($C^n$) and a detail signal ($D^n$). These approximate signal and detail signal will be further decomposed at the first scale level resulting into four coefficients. i.e. one approximation coefficient (A), three details coefficients (horizontal component (H), vertical component (V), and diagonal component (D)). This considered as one level of decomposition [19]. Further, approximation coefficient A can be decomposed into four components, and these decomposing and computing process can be continued till the desired scale of decomposition. In the present work, unaged and gamma irradiated samples surface images (acquired by the surface profilometer) were analysed by 2D MRSD at the different resolutions and orientations.

One of the important factors affecting the processing of signal using wavelet transform is the selection of proper mother wavelet. Different selection methods can be utilised to select the proper mother wavelets for signal processing with wavelet transform. In the present work, based on the high value signal to noise ratio (SNR), and low value of the mean square error (MSE) between original signal and reconstructed signal, appropriate mother wavelet was selected. Table 1 shows the SNR and MSE value calculated using different types of mother wavelet. It was observed that among all the mother wavelet function, Daubechies (db) wavelets showed the highest SNR value and lowest MSE value for the surface profilometer signal. Further, SNR and MSE value was calculated for the different orders of db wavelets, as shown in table 2. It was observed that surface profilometer signal processed using Daubechies wavelets of order 4 (db4) showed the highest signal to noise ratio value and lowest mean square error value. As a result, in the present work, wavelet transform was performed using db4 for evaluating the surface profilometer of the unaged and gamma irradiated surface epoxy-alumina nanocomposites.

### Table 1. SNR and MSE for different types of mother wavelets.

| Mother Wavelet | SNR (db) | MSE       |
|----------------|----------|-----------|
| sym           | 29.9017  | 11.7636   |
| db            | 32.4909  | 9.0714    |
| fk            | 27.4134  | 20.8628   |
| bior          | 30.1176  | 11.1932   |
| coil          | 30.7253  | 10.7316   |

#### 2.5. Fractal theory and Lacunarity analysis

Fractal theory can be adopted to classify and quantify the nature of disorder in the self-similar objects [21]. Fractal dimensions provides the quantitative number proportional to the surface roughness of the materials that can be used for classifying the materials based on their surface property. In the present work, fractal dimension for all the unaged and gamma aged sample was calculated using box counting method [22]. Box counting involves the calculation of number of boxes n(r) required to cover the surface of the material. By varying the box size r, different value of the n can be obtained, and fractal dimension D can be obtained as

![Figure 3. Schematic diagram of the 2D MRSD process.](image-url)
Lacunarity shows the inhomogeneity and non-uniformity in the structure of the surface of material. More the lacunarity, more the inhomogeneous surface which can be related to roughness of the material surface. In the present work lacunarity \( L \) can be calculated for the unaged and gamma aged samples using
\[
L = \frac{\sum M^2 \sum Q(M, r)}{\left( \sum M \sum Q(M, r) \right)^2},
\]
where, \( Q(M, r) \) is the probability function obtained by the ratio of number of boxes \( n(r) \) and total number of boxes with box size \( r \) and mass \( M \). The calculated lacunarity was compared with fractal dimension and the surface roughness of the samples.

3. Results and discussions

3.1. Surface potential decay measurement and trap distribution analysis

Figure 4 shows the surface potential decay characteristics of the unaged and gamma irradiated samples. The surface potential variation exhibits exponential decay and can mathematically be represented as
\[
V = V_0 e^{-\lambda t},
\]
where \( V_0 \) is the initial potential and \( \lambda \) is the decay rate. The decay rate of the unaged samples and for gamma irradiated samples are shown in tables 3 and 4. It was observed that increment in the wt% of alumina nano filler enhanced the decay rate. Also, the decay rate under + DC voltage was found to be higher than − DC voltage. Du et al observed the similar variation in decay rate with the epoxy titania nanocomposites [24]. Addition of alumina nanoparticles altered the localised surface states and the surface detrapping resistance, which results into the increment of decay rate in the nanocomposites. Increase in the dosage level of gamma irradiation, increased the decay rate for all the samples (tables 3 and 4). Gamma irradiation can cause oxidation and chain scission reaction with the polymer causing formation of the carbonyl and hydroxyl group in the nanocomposites. These carbonyl and hydroxyl group enhances the level of shallow traps which consequently increased the surface charge carrier mobility resulting into increase in the decay rate [25].

The trap distribution can be evaluated using the surface potential decay characteristics [26] as
\[
N(E) = \frac{2 \varepsilon_o \varepsilon_m}{qL^2kT\rho(E)} \frac{dV}{dt},
\]
where \( q \) is the electron charge, \( L \) is sample thickness, \( k \) is the Boltzmann constant, \( T \) is the absolute temperature, \( t \) is time, and \( \rho(E) \) is occupancy rate of initial electrons.

The trap depth \( \Delta(E) \) can be represented as
\[
\Delta(E) = E_C - E_M = kT \ln (\nu t),
\]
where \( E_C \) is conduction band energy and \( E_M \) demarcation energy, \( k \) is the Boltzmann constant, \( \nu \) is the escape frequency of electron (10^{12} Hz) and \( T \) is the absolute temperature. Figure 5 shows the trap distribution characteristics for unaged and gamma irradiated epoxy alumina nanocomposites. The peak of the trap characteristics was identified as trap depth and its value for epoxy alumina nanocomposites is shown in tables 3 and 4. Left shift in the trap depth was observed on the incorporation of alumina nanofiller and on exposing the samples to gamma rays. Reduction in the trap depth indicated the formation of a greater number of shallow traps which lead to the reduction in surface detrapping resistance and enhancement in the charge detrapping process. Fast detrapping of charge carrier lead to the increment in the decay rate. Comparing the behaviour of decay rate and trap depth, they show inverse correlation.
3.2. Surface morphology analysis using wavelets

Figure 6 shows the 1D MRSD of the surface profile of the pure epoxy sample. Daubechies wavelet of order 4 was used to decompose the surface profile signal into seven level of decomposition and corresponding standard deviation of the approximation coefficient (high pass filter) and details coefficients (low pass filter) were:

Table 3. Variation of decay rate and trap depth of unaged and gamma irradiated samples under +DC voltage.

| Samples    | Unaged samples | 5 kGy gamma irradiated samples | 10 kGy gamma irradiated samples | 15 kGy gamma irradiated samples |
|------------|----------------|--------------------------------|----------------------------------|----------------------------------|
|            | Decay rate (λ) | Trap depth (eV)                | Decay rate (λ)                   | Trap depth (eV)                  | Decay rate (λ)                   | Trap depth (eV)                  |
| Pure epoxy | 0.0048         | 0.852                          | 0.0062                           | 0.8404                           | 0.0073                           | 0.8352                           | 0.0096                           | 0.8284                           |
| 1 wt%      | 0.0053         | 0.846                          | 0.0071                           | 0.836                            | 0.0079                           | 0.8336                           | 0.0102                           | 0.8271                           |
| 3 wt%      | 0.0054         | 0.843                          | 0.0074                           | 0.8348                           | 0.0084                           | 0.8319                           | 0.0137                           | 0.8191                           |
| 5 wt%      | 0.0057         | 0.842                          | 0.0086                           | 0.831                            | 0.0092                           | 0.8294                           | 0.0144                           | 0.8176                           |

Table 4. Variation of decay rate and trap depth of unaged and gamma irradiated samples under -DC voltage.

| Samples    | Unaged samples | 5 kGy gamma irradiated samples | 10 kGy gamma irradiated samples | 15 kGy gamma irradiated samples |
|------------|----------------|--------------------------------|----------------------------------|----------------------------------|
|            | Decay rate (λ) | Trap depth (eV)                | Decay rate (λ)                   | Trap depth (eV)                  | Decay rate (λ)                   | Trap depth (eV)                  |
| Pure epoxy | 0.0045         | 0.854                          | 0.0059                           | 0.8421                           | 0.0068                           | 0.8374                           | 0.0088                           | 0.8306                           |
| 1 wt%      | 0.0049         | 0.849                          | 0.0064                           | 0.8388                           | 0.0075                           | 0.8348                           | 0.0091                           | 0.8299                           |
| 3 wt%      | 0.0051         | 0.846                          | 0.0069                           | 0.8367                           | 0.0077                           | 0.834                           | 0.0132                           | 0.8201                           |
| 5 wt%      | 0.0054         | 0.841                          | 0.0075                           | 0.8347                           | 0.0088                           | 0.8306                           | 0.0141                           | 0.8183                           |

3.2. Surface morphology analysis using wavelets

Figure 6 shows the 1D MRSD of the surface profile of the pure epoxy sample. Daubechies wavelet of order 4 was used to decompose the surface profile signal into seven level of decomposition and corresponding standard deviation of the approximation coefficient (high pass filter) and details coefficients (low pass filter) were.
calculated. Figure 7 shows the variation in standard deviation of approximate coefficient and detail coefficient measured for epoxy-alumina nanocomposites. Decrement in standard deviation of both coefficients for epoxy-alumina nanocomposites started at the lower levels of decomposition as compared to the pure epoxy sample. Standard deviation was observed to be the highest for the 3 wt% sample for both the coefficients.

The effect of gamma irradiation on the surface roughness profile of the epoxy-alumina nanocomposites were analysed. It was observed (in figure 7) that standard deviation for both the coefficients of 15 kGy gamma irradiated pure epoxy sample were less than the unaged one. Both coefficients found to decrease after the decomposition level of 6. 3 wt% gamma irradiated sample showed the higher standard deviation in approximation coefficient for all the levels of the gamma irradiation. Pure epoxy sample didn’t show much variation in detailed coefficient value for lower dosage levels of gamma rays but at higher dosage level i.e. 15 kGy, detailed coefficient value increased. The characteristics was converse with nanocomposites material. These variation in the standard deviation depends on the variation in the surface profile of the samples.

On gamma irradiation, variation in the amplitude of the surface profile will be more, as a result, variation in the approximation and detail coefficient at different decomposition level will be more resulting into increment in standard deviation value. During gamma irradiation, different crosslinking and oxidation reaction takes place in the epoxy-alumina nanocomposites. In case of pure epoxy sample, oxidation reaction lead to the loosening and breaking of polymeric bond which results in the increment of amplitude level of the surface profile. Increased amplitude of the surface profile enhanced the variation in detail coefficient value which results into the increment of standard deviation. Similar condition would be observed with the lower dosages of gamma irradiated nanocomposite samples. Above certain level of gamma irradiation i.e. 15 kGy, crosslinking reaction was dominant which lead to little reduction in amplitude level of surface profile level [27]. These less variation in amplitude of surface profile for 15 kGy gamma ray irradiated nanocomposites, lead to the reduction in the variation in the detail coefficient value, resulting into the reduction of standard deviation. Thus, the decrement in standard deviation after particular decomposition level for both the coefficients was same for all the gamma irradiated samples.

Hierarchical information of the surface morphology of epoxy-alumina nanocomposites were analysed using 2D MRSD (db4 wavelet) on the surface images captured by surface profilometer. 2D MRSD gives the information on different changes in the surface morphology at different orientations and resolutions.
Figure 8 shows the horizontal, vertical, and diagonal details of the surface images of the unaged pure epoxy sample, obtained as a result of 2D MRSD in which db4 wavelet was used as mother wavelet. Decomposition level for both the samples were same as per standard deviation analysis and 1D MRSD analysis. Smooth surface morphology at every resolution was observed for the unaged pure epoxy sample as compared to the gamma irradiated pure epoxy sample. Similar 2D MRSD analysis was carried out for the other samples and it was observed that on addition of alumina nanofiller, surface morphology of the unaged nanocomposites was getting smoother. And also increment of dosage level of gamma irradiation, increased the roughness of the sample but at dosage level of 15 kGy, nanocomposites surface was observed to be smoother compared to the 5 kGy and 10 kGy irradiated nanocomposites. These change in the surface roughness of the epoxy-alumina nanocomposites can be more precisely understood by the 3D plot of the sum of these horizontal, vertical, and diagonal details (high frequency components).

Figure 9 shows the 3D plot of the surface of the unaged pure epoxy sample and 15 kGy gamma irradiated pure epoxy sample. It could be clearly seen that sample became rough for the gamma irradiated pure epoxy sample at every analytical resolution as compared to the unaged samples.
The characteristic variation in the roughness of the nanocomposites can be quantitatively analysed by calculating the surface roughness factor \( R_s \) at each decomposition level as:

\[
R_s = \sqrt{\frac{\sum_{i=1}^{n} (X_i - X_m)^2}{n}},
\]

where, \( X_i \) is the sum of high frequency components at positions \( i \), \( X_m \) is the mean of \( X_i \) and \( n \) is the total number of \( X_i \). Surface roughness factor was calculated for all the samples and is shown in figure 10. The variation in the roughness of the samples was clearly observed on addition of alumina nanoparticles and at different levels of gamma rays ageing. The decrement in the roughness of sample on addition of alumina nano filler at different decomposition level can be attributed to the strong interfacial bonding between the epoxy matrix and alumina nanoparticles and increment in the adhesion of the nanocomposites to the surface which leads to the reduction in the surface concentration of the nanoparticles \[28\]. Different dosage of gamma irradiation altered the roughness value of pure epoxy sample significantly. Gamma irradiation led to the initiation of multiple internal processes like cross-linking, chain scission process, different polymer radicals formation, etc \[29\] and due to rupture of these weak covalent polymeric bond, led to the increment in roughness value for pure epoxy sample. In case of the nanocomposites, marginal increment in the roughness factor was observed on increment in the dosage rate but above certain level (15 kGy) very minimal change in the roughness value was observed. In general, among the unaged and aged 1 wt%, 3 wt%, and 5 wt% nanocomposites, 3 wt% nanocomposites showed the highest roughness value.

3.3. Fractal dimension and lacunarity analysis
The change in the surface morphology of the nanocomposites were more precisely observed in the 3D plot of the sample surface at different analytical resolutions in the above analysis. Gao et al have clearly indicated that 3D...
plot of surface morphology exhibited fractal character [30]. Fractal dimensions of the surface profile of all the unaged and aged samples were evaluated using box counting method. The slope of the linear part of the curve between the number of boxes versus box size provides the fractal dimension [22]. The fractal dimensions for all the unaged and gamma aged samples, were calculated based on box counting technique and is shown in table 5. It was observed that addition of alumina nanofiller decreased the fractal dimension value and this decrement can be attributed to reduction in the surface roughness value on the increment in wt% of alumina nanofiller to the base epoxy resins. Similar variation in the fractal dimensions for gamma irradiated samples were observed and these variations were consistent with the surface roughness value.

Lacunarity of the surface profile of all unaged and gamma irradiated nanocomposite samples were calculated and provided in table 5. Lacunarity shows the inhomogeneity in the structure of the sample surface and it increases with the increase in surface roughness. Lacunarity reduces with increase in wt% of alumina in epoxy resin. Also, on irradiation, irrespective of wt% of alumina added nanocomposites, a marginal increase in lacunarity is observed. As a result, lacunarity and fractal dimension showed the inverse correlation, as observed in table 5.

4. Conclusions

The important conclusions derived from the present study:

1. Surface potential decay rate increased on addition of alumina nanofiller and for gamma irradiated samples. Left shift in the trap distribution characteristics was observed on increase in the wt% of alumina nanofiller in epoxy nanocomposites and also on gamma irradiation, which indicates the formation of shallower traps.
2. Daub4 wavelet found to be more suitable as mother wavelet for surface roughness measurement studies 1D and 3D Surface profile analysis of the unaged and gamma aged alumina nanocomposites adopting MRSD technique indicated that, 3 wt% epoxy alumina nanocomposites showed the highest roughness value.

3. Surface roughness factor was reduced with the increment in the wt% of alumina nanofiller. Irrespective of wt% of nano alumina in epoxy resin, on gamma irradiation, the surface roughness factor has shown marginal increase in value, at each level of decomposition.

4. Fractal dimension of the surface profile of all unaged and gamma irradiated epoxy nanocomposites was observed to be proportional with surface roughness value and it showed inverse correlation with the lacunarity value.

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Table 5. Fractal dimension and lacunarity of unaged and gamma irradiated samples.

| Sample            | Unaged | 5 kGy    | 10 kGy   | 15 kGy   |
|-------------------|--------|----------|----------|----------|
| Pure epoxy        | 1.824  | 1.908    | 1.951    | 1.977    |
| 1 wt%             | 1.779  | 1.874    | 1.886    | 1.890    |
| 3 wt%             | 1.764  | 1.882    | 1.871    | 1.868    |
| 5 wt%             | 1.746  | 1.869    | 1.919    | 1.885    |
| FD: Fractal Dimension, LY: Lacunarity.

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Figure 10. Surface roughness factor of the (a) unaged, (b) 5 kGy, (c) 10 kGy, and (d) 15 kGy gamma irradiated epoxy alumina nanocomposite samples at different analytical resolutions.
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