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# ENHANCING THE MECHANICAL, THERMAL AND ELECTRICAL PROPERTIES OF ALUMINA-MWCNT HYBRID NANOFILLER REINFORCED EPOXY COMPOSITES

## IZBOLJŠANJE MEHANSKIH, TOPLOTNIH IN ELEKTRIČNIH LASTNOSTI EPOKSIDNEGA HIBRIDA OJAČANEGA Z NANO POLNILOM NA OSNOVI ALUMINIJEVEGA OKSIDA IN VEČ STENSKIH OGLJIKOVIH NANO CEVK

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In this work, alumina and multi-wall carbon nanotube (MWCNT) hybrid nanofiller reinforcing pure epoxy at varying weight fractions of (0.1, 0.2, 0.3, 0.4 and 0.5) *w*/% is investigated to enhance the mechanical, electrical and thermal properties. The porosity, tensile strength, electrical and thermal conductivity of epoxy hybrid nanocomposites are studied after the effects of the alumina-MWCNT hybrid nanofillers. The interfacial adhesion and mechanical interlocking between the hybrid nanofillers and epoxy are greatly increased with the addition of alumina and MWCNTs, thus leading to an improvement in the mechanical properties. Additionally, a uniform distribution of hybrid nanofillers results in a larger increase in the thermal and electrical conductivity. The presence of voids in specimens is gradually decreased when the nanofiller content is increased up to 0.3 *w*/%. The alumina-MWCNT reinforcement significantly improves the tensile strength, by 88 %, compared with pure epoxy. Similarly, the electrical and thermal conductivity increase by 85 % and 64 %, respectively, when compared with low weight fractions of the hybrid nanofiller. Agglomeration during the fabrication of nanocomposites is manageable but it is inevitable. During the formation of chains and networks, the alumina-MWCNT reinforcement of pure epoxy greatly influences the thermal conductivity. This strategy provides a prospective new concept for the use of epoxy and its composites in structural and thermal engineering applications.

Keywords: hybrid nanofillers, MWCNTs, alumina, mechanical properties

Opisana je raziskava vpliva ojačitve čiste epoksidne smole z delci aluminijevega oksida in nano delci iz več stenskih ogljikovih nano cevčic (MWCNTs; angl.: multi wall carbon nanotubes) na mehanske, električne in termične lastnosti. Izdelali so hibridne polimerne nano kompozite z različnimi masnimi deleži hibridnega nano polnila iz aluminijevega oksida in MWCNT (0,1, 0,2, 0,3, 0,4 in 0,5) *w*/%. Nato so določili poroznost, natezno trdnost, električno in toplotno prevodnost epoksidnih hibridnih nano kompozitov ter določili vpliv količine dodanega nano polnila na te latnosti. Medmejna adhezija in mehanska povezava med epoksijem in nano polnilom se je močno povečala z njegovim dodatkom, kar je precej izboljšalo mehanske lastnosti izdelanih nano kompozitov. Dodatno sta se zaradi enakomerne porazdelitve delcev hibridnega nano polnila po prostornini epoksidne smole povečali tudi toplotna in električna prevodnost kompozitov. Prisotnost praznin oziroma por v preizkušancih se je postopno zmanjševala s povečevanjem vsebnosti nano polnila do 0,3 *w*/%. S hibridnim polnilom na osnovi Al-oksida in MWCNT ojačanim nano kompozitom se je v primerjavi s čistim epoksijem močno povečala natezna trdnost (do 88 %). Podobno sta se izboljšali tudi električna in toplotna prevodnost kompozitov za do 85 % oziroma 64 % v primerjavi z nizkim deležem nano polnila. Aglomeracija med izdelavo kompozitov je neizogibna vendar jo je možno obvladati. Na toplotno prevodnost kompozitov najbolj vpliva tvorba verig in zamreženje polnila s čistim epoksijem. S predstavljeno strategijo izdelave nano polimernih kompozitov se ponuja nov koncept uporabe epoksija in njegovih kompozitov za strukturne in termične inženirske aplikacije.

Ključne besede: hibridna nano polnila, večstenske ogljikove nano cevke, aluminijev dioksid, mehanske lastnosti

## 1 INTRODUCTION

Polymer matrices and nanofillers with dimensions in the nanometre range have shown potential for various engineering applications. The high aspect ratio and surface-to-volume ratio of nanosized fillers lead to improved material properties and structural stability, as well as unique functions. The use of nanoscale graphite and ceramic by-products such as carbon nanotubes and alumina as fillers further enhances the advantages of polymer nanocomposites. Individual properties of a material are based on its constituents and the physical property can be improved with the reinforcement of fillers acting as composites so that it can be widely used in diverse applications.[1–3] Polymer composites are drawing a lot of attention due to their easy fabrication and cost effectiveness compared to other composites.[4,5] Integration of nanofillers into a regular polymer matrix resulted in polymer nanocomposites, significantly employed in various engineering applications including aerospace, marine and automotive industries, construction, sports and en-

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ergy storage.[6] Nanosized fillers exhibit superior interface bonding with a polymer matrix, thus improving the structural stability and material property due to their high aspect and surface-to-volume ratios.[7,8] Pure epoxy exhibits its predominant properties when nanosized particles such as boron nitride, carbon nanotubes, silicon dioxide, alumina nitride, zinc oxide, alumina, graphite and hallosite nanotube (HNTC) are added as reinforcements.[9]

There are many more engineering applications where alumina is introduced as a matrix element and such composites are widely employed due to their high strength, microstructural stability and elevated thermal resistance.[10] Alumina reinforcement of polymers produces better thermal, mechanical and electrical properties. With ceramic reinforcement, a higher wear resistance, exceptional hardness and good corrosion resistance can be achieved at a low cost.[11] In order to get particular customized and improved properties of a polymer, alumina-MWCNT reinforced epoxy hybrid polymer nanocomposites are used. A significant enhancement in the composite properties is achieved using hybrid nanofillers as the reinforcement, which have been compared with pure epoxy. The term hybrid composite indicates the use of more than one material as the reinforcement or particulates in multiple physical forms as a single reinforcement. The homogeneous mixture and interlock bonding architecture of the reinforcement in a polymer matrix can be employed to significantly enhance the physical properties of the host matrix with synergistic strengthening effects. As compared to singular or mono-reinforced nanocomposites, hybrid nanocomposites exhibit improved properties.

For the development of nanocomposites, MWCNTs are very attractive nanofillers due to their significant properties like thermal, electrical and noteworthy physical properties.[12,13] Alumina has significant structural properties, providing unique physical, thermal and mechanical properties when used as the reinforcement. Epoxy-based hybrid nanocomposites with ceramic and carbonaceous nanofillers like alumina and multi-wall carbon nanotubes possess the properties of pure epoxy as well as the properties of the nanofillers. To improve the properties of a hybrid nanocomposite, a significant interfacial bonding between the hybrid nanofillers and the polymer material is required. In epoxy-based hybrid nanocomposites, the hybrid nanofillers including carbon nanotubes and alumina are the best suitable reinforcements of pure epoxy. In the manufacturing of nanocomposites, carbon nanotubes are widely used as nanofillers. The effect of the van der Waals attraction force in carbon nanotubes leads to the agglomeration of nanofillers.[14] Alumina has a 3D morphology and high aspect and surface-to-volume ratios, which help it to integrate with a neat matrix and improve its properties. Due to the excellent mechanical properties, alumina is used as the strengthening reinforcement element in composites. Significant physical and mechanical properties and chemical stability of carbon nanotubes and alumina allow the development of three-dimensional nanostructure building blocks.[15,16] Multi-layer cylindrical graphene in the form of a tube structure with a diameter of less than 2 nm is called multi-wall carbon nanotubes. The modulus of elasticity and tensile strength of multi-wall carbon nanotubes in the axial direction can be up to 1 TPa and 63 GPa, respectively. Multi-wall carbon nanotubes possess a large aspect ratio of about 1000:1. MWCNTs exhibit a thermal conductivity of 3500 N/mK at atmospheric temperature and the electrical resistivity is in the order of $10^{-4}$ Ω at room temperature. Furthermore, MWCNTs exhibit significant elasticity of up to 20 %. It is expected that an MWCNT-alumina hybrid provides an enhancement of various properties. In order to address the foremost property enhancement of a polymer, enormous investigations need to be carried out by researchers to achieve the mechanical properties required for advanced structural applications without a loss in the toughness. However, the mechanical properties of thermosetting polymers such as the modulus of elasticity and yield stress are reduced during the addition of thermoplastic polymers.

Furthermore, enormous investigations of the reinforcement of low- as well as high-aspect-ratio nanoparticles in epoxy resins were carried out to improve the potential properties such as wear resistance, electrical resistivity and mechanical characteristics of polymers.[17] Carbon-nanotube and silver-particle reinforced epoxy became a good electrically conducting polymer. The epoxy reinforced with black carbon exhibits heat normalization during elevated-temperature applications. In the field of lightweight-structure applications, namely automotive, medical-instrument, aerospace, marine industries, etc., nanofiller-reinforced polymer composites occupy a significant space and also have a high strength-to-weight ratio. However, the use of fibres with nanofillers, macro- and nanosized organic and inorganic fillers, reinforcing epoxy has some advantages and restrictions. But in recent days, the use of oxide nanofillers for reinforcing epoxy resins has gained significant attention due to the chemical stability, high modulus value, cross-linking and aspect ratio. The use of carbon and oxide nanofillers (a hybridization filler) for reinforcing epoxy resin is gaining more attention for the development of a multifunctional structural composite material with enhanced mechanical characteristics.

Three types of oxide nanoparticle hybridized in carbon nanotubes, namely titanium oxide, silicon zirconium oxide and alumina oxide, are used to improve the mechanical properties.[18] Homogeneous dispersions of hybrid nanoparticles improve the properties of epoxy composites. A qualitative homogeneous dispersion of the nanoparticles in pure epoxy governs the toughening properties of the epoxy. To attain a homogeneous dispersion of nanoparticles in the matrix, various dispersion methods are employed, namely mechanical stirring, solution mixing, shear mixing, melt mixing and ultrasonication. These methods have been utilized to achieve dispersion in the epoxy matrix. Initially, the reason for the change in mechanical properties is determined by analysing the internal structures of nanocomposite specimens, such as filler alignment, filler distribution and interface between the filler and matrix. We place a significant emphasis on assessing the impact of internal voids or porosity on the interface area between the filler and matrix, while assuming no change in the interface adhesion. This investigation focusses on various weight fractions of MWCNT-alumina hybrid nanoparticles reinforcing pure epoxy and investigates the mechanical properties as well as electrical and thermal conductivity of the epoxy hybrid nanocomposite; a fractured surface morphological analysis is also presented.

## 2 EXPERIMENTAL PART

### *2.1 Epoxy as the polymer matrix*

In the current research work commonly used polymer epoxy resin is the matrix for the manufacturing of a structural material. The use of the epoxy matrix results in a dual-element system. The first element is epoxy resin and the second component is the curing agent or hardener. A multidimensional cross-linked network can be developed in epoxy resin when a solidification process is carried out using the curing agent. Cross-linked bisphenol A diglycidyl ether (BADGE) epoxy resin is frequently used for widely spread structural applications. Curing agents are broadly classified into carboxylic acid, anhydrides, amides and amines. Based on the required properties and applications, the curing agent is chosen. In room-temperature solidification processes amines are used generally.

### *2.2 Synthesis of alumina-MWCNT hybrid nanofillers*

Nanosized multi-wall carbon nanotubes were purchased from BT Corp. Pvt. Ltd., India. The MWCNT average outer diameter was about 25–35 nm, the length was 15 µm and the specific surface area was 180–200 $m^2 \cdot g^{-1}$. The preparation of alumina-MWCNT hybrid nanofillers was accomplished based on the literature review with a considerable modification based on hybrid applications. Auqa regia solution was used to clean all the glass ware used for this hybrid nanofiller preparation. The MWCNTs were first purified by dissolving 2.5 g of them in 60 mL of concentrated nitric acid (75 *w*/%) at 90 °C for 18 h, filtering and washing them in ultrapure water, and then dissolving them in 50 mL of HF (40 *w*/%) at 70 °C for 24 h. To stabilize the turbid liquid pH value in a range of 7.0, ultrapure water was used for socking and drying, carried out at 100 °C for 12 h. Under 100 $min^{-1}$ stirring condition, the purified MWCNTs were refluxed at 140 °C for 2 h with nitric acid (75 *w*/%) and sulphuric acid (80 *w*/%). The functionalized substance was filtered and socked in high-purity water to stabilize the pH value of 7.5 and kept in the oven for 24 h for drying. The required quantity of functionalized MWCNTs was dispersed in high-purity water and agitated with a magnetic shaker for 6 h to attain desirable dispersion. Afterwards, 7.8 g of $Al(NO_3)_3 \cdot 9H_2O$ were appropriately dissolved in high-purity water. The $Al(NO_3)_3$ solution was dropwise added into dispersed functionalized MWCNTs. During the addition of successive drops, sufficient time allowed for the alumina to properly dissolve and occupy the functionalized MWCNT surfaces. After that, the suspension was dried at 105 °C. The resulting synthesized CNT-alumina was kept in the oven at 130 °C overnight for the drying process. A scanning electron microscope was used to identify the CNT-alumina hybrid nanopowder surface, and XRD patterns (**Figure 1**) were taken at room temperature with $2\theta$ ranging from 0° to 90°, a step rate of 0.05° $s^{-1}$, an operating target voltage of 30 kV and a tube current of 100 mA. The prepared hybrid nanocomposites were sealed in glass containers for subsequent testing.

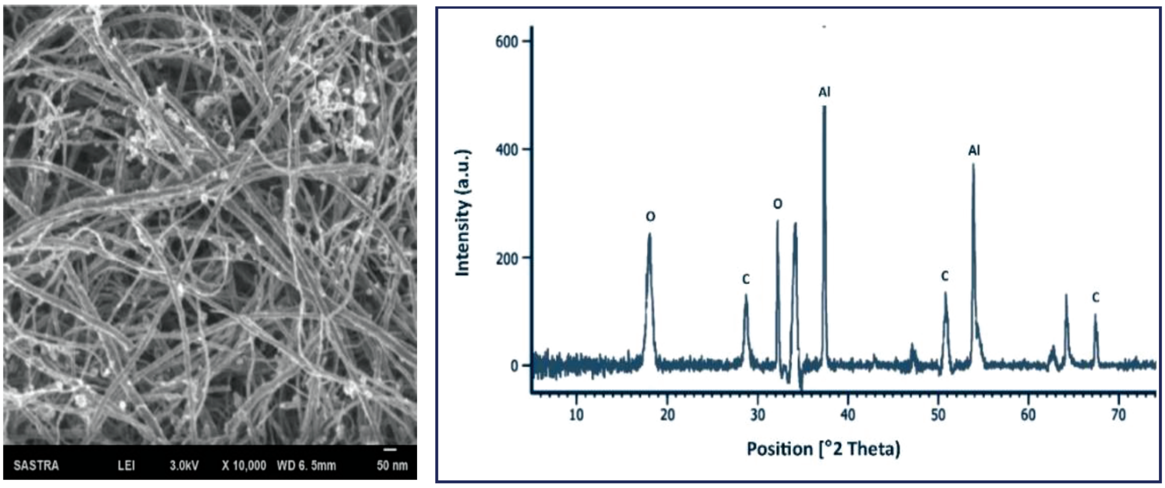

**Figure 1:** SEM image and XRD pattern of CNT-alumina nanocomposites

### *2.3 Epoxy-alumina-MWCNT hybrid nanocomposite sample preparation*

The required quantity (ml) of epoxy was placed into a conical beaker and weighed with an electronic balance machine to calculate the weight of the epoxy. The epoxy was heated up to 60 °C and kept in a sonicator. The process frequency was set to 30 kHz. The synthesized hybrid nanofillers were gradually added into pure epoxy, using different weight fractions of (0.1, 0.2, 0.3, 0.4 and 0.5) *w*/%. The pure epoxy and various weight fractions of hybrid nanofillers were labelled and presented in **Table 1**. The sonication process was continued for 30 min with a power of about 450–500 W and a frequency range of 100–150 KHz to ensure a homogeneous dispersion of hybrid nanofillers in the host matrix. The epoxy hybrid nanocomposite suspension was kept in a vacuum chamber for 2 h for evacuating the vacuum bubbles. Araldite HY951 was added in a volume ratio of 10:1. The epoxy hybrid nanocomposite solution was poured into an acrylic sample mould to make a test specimen and for each composition, five specimens were fabricated without changing the manufacturing method or conditions.

**Table 1:** Composites of pure epoxy reinforced with various weight fractions of alumina-MWCNT hybrid nanofiller

| Composition: Pure epoxy | Label: PE |
|---|---|
| Pure epoxy + 0.1 *w*/% of alumina MWCNT hybrid nanofillers | PEHNF1 |
| Pure epoxy + 0.2 *w*/% of alumina MWCNT hybrid nanofillers | PEHNF2 |
| Pure epoxy + 0.3 *w*/% of alumina MWCNT hybrid nanofillers | PEHNF3 |
| Pure epoxy + 0.4 *w*/% of alumina MWCNT hybrid nanofillers | PEHNF4 |
| Pure epoxy + 0.5 *w*/% of alumina MWCNT hybrid nanofillers | PEHNF5 |

### *2.4 Porosity measurement*

The porosity clusters of the nanocomposites were computed using the visual inspection method. The epoxy alumina-MWCNTs hybrid nanocomposite specimens were cut into 16-mm diameter discs using a die punching machine as shown in **Figure 2a**. The discs were weighted with a 0.001 accuracy weighing machine to calculate the mass and thickness and they were measured using a micrometer, assuming that there was no porosity in the nanocomposite discs. For alumina-MWCNT nanocomposites with alumina volume fraction $\varphi_a$ and MWCNT volume fraction $\varphi_c$ the theoretical $M_t$ was calculated as $M_t = (\varphi_a \rho_{alumina} + \varphi_c \rho_{mwcnt} + (1 - (\varphi_a + \varphi_c)\rho_{epoxy}))v_t$ where $\rho_{alumina}$, $\rho_{mwcnt}$ and $\rho_{epoxy}$ refer to the density of alumina, MWCNTs and epoxy, respectively, and $v_t$ is the volume of the disc. The porosity $p$ is expressed as

$$p = 1 - \frac{M_m}{M_t} \tag{1}$$

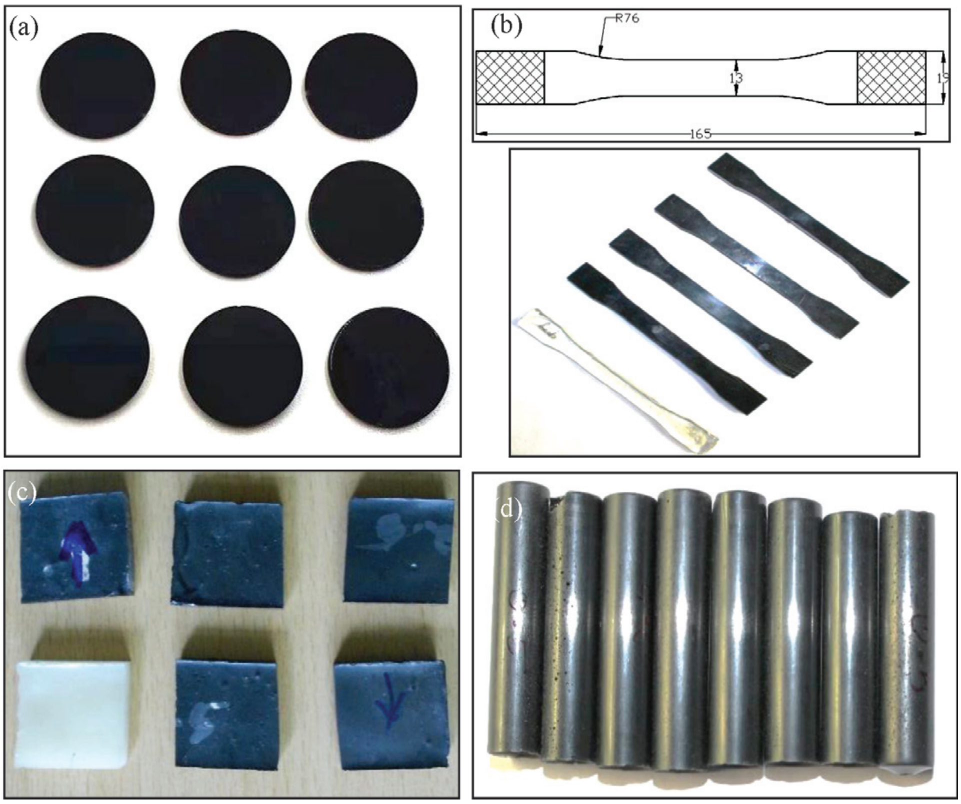

**Figure 2:** Test samples for: a) porosity measurement, b) tensile test, c) electrical conductivity measurement and d) thermal conductivity measurement

where
$M_m$ = measured mass of the hybrid composites
$M_t$ = theoretical mass of the hybrid composites

The porosity is known for causing imperfection, thus affecting the stress concentration and leading to poor mechanical properties.

### 2.5 Tensile strength

Epoxy hybrid nanocomposite specimens were fabricated in accordance with the ASTM D638 standard as shown in **Figure 2b**. They were subjected to a tensile test using a Shimadzu tensile test machine with a load of 0.1 N mm/min. The tensile test was performed at room temperature with an overhead speed of 5 mm/min. Five specimens with the same composition were used to get the average value of the tensile strength.

### 2.6 Electrical conductivity measurement

The computer-controlled two-wire method was used to measure the electrical conductivity (Keithley 6221DC, Tektronix, USA) of the hybrid nanocomposite test samples. The specimen size was (25 × 25 × 2) mm and the tested surface was coated with a silver functional coating to improve the conductivity as shown in **Figure 2c**. The functional coating was applied to the substrate through a physical vapor deposition process. This is done by charging a sputtering cathode and creating a plasma, which causes the material to be ejected from the target surface with the following specifications: a vacuum of $3 \times 10^{-2}$ mbar, a voltage of 1.5 kV, a current of 30 mA, a deposition of 25 nm/min and a grain size of = 5 nm. A silver-coated specimen was connected to the circuit board to determine the electrical conductivity ($\sigma$) with the following equation:

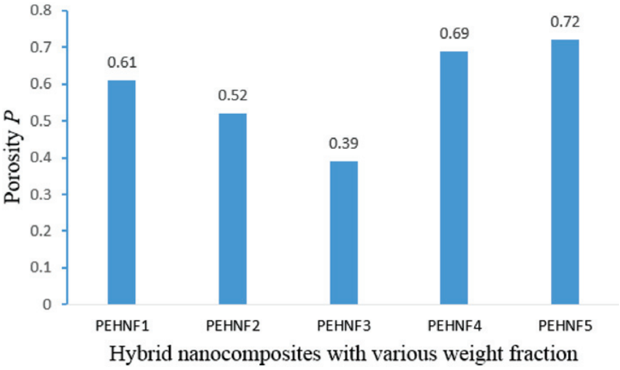

**Figure 3:** Porosity of the pure epoxy/alumina-MWCNT hybrid nanocomposites

$$\sigma = L/RA \tag{2}$$

where
$L$ = Length of the test sample
$A$ = Test sample cross-sectional area
$R$ = Resistance

### 2.7 Thermal conductivity measurement

The thermal conductivity of epoxy hybrid nanocomposites was measured using a laser flash apparatus. The test sample dimension was Ø 6 mm and the length was 40 mm as shown in **Figure 2d**. For each composi-

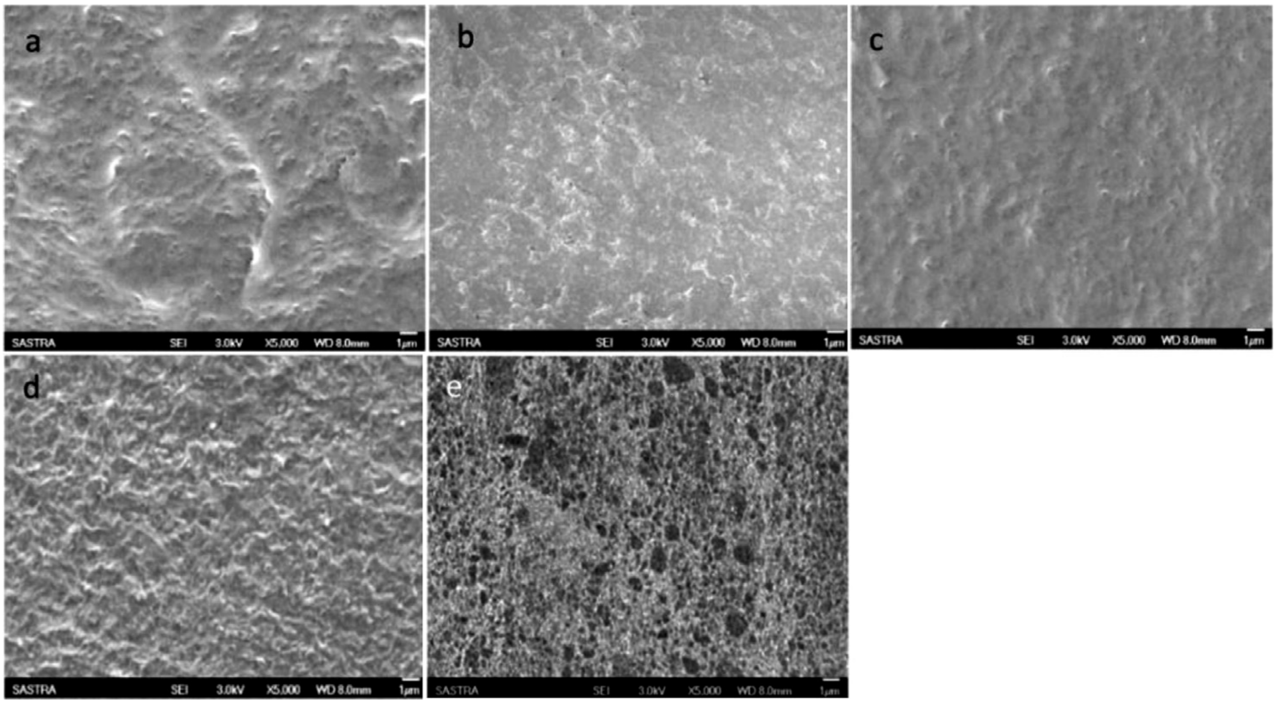

**Figure 4:** SEM images show the porosity of: a) PEHNF1, b) PEHNF2, c) PEHNF3, d) PEHNF4, e) PEHNF5

tion, five samples were taken and the average values were recorded at room temperature. The thermal conductivity was measured using the following equation:

$$\lambda = \alpha \times C_p \times \rho \qquad (3)$$

where
$\alpha$ = Thermal diffusivity coefficient ($m^2/s$)
$C_p$ = Specific heat capacity at constant pressure (J/(kg-k)
$\rho$ = Density of the composite ($kg/m^3$)

## 3 RESULTS AND DISCUSSION

### 3.1 Porosity analysis

The porosity (or voids) was investigated on the nanocomposites with different weight fractions. The voids of alumina-MWCNT polymer nanocomposites were characterized by both observing their cross-sectional morphology and quantifying the amount of voids. A surgical blade was used to slice the open samples of pure epoxy with various volume fractions of alumina-MWCNTs for viewing the internal voids. For each form of nanocomposite, the porosity was inversely proportional to the volume fraction of hybrid nanofillers. This indicates that small spaces caused by air interference are created by filler-to-filler contacts, which are the main factors for generating voids.

Equation 1 was used to calculate the porosity. The theoretical mass ($m_t$) was computed using the densities of each component (i.e., alumina = 2.960 $g/cm^3$, MWCNTs = 1.670 $g/cm^3$ and epoxy = 1.165 $g/cm^3$) whereas the actual mass ($m$) was measured using a weighing scale. The characterization of alumina-MWCNT polymer nanocomposites was analysed by quantifying the amount of voids and observing their surface morphology. The presence of void in the specimens varies with the reinforcement of the nanofillers with different weight fractions. Interestingly, it was observed that the voids were gradually decreasing when the nanofiller content increased up to 0.3 *w*/% (**Figures 4a** to **4c**). Due to the excessive addition of hybrid nanofillers that bundled together in the host matrix, with the additions of 0.4 *w*/% and 0.5 *w*/% of the nanocomposites, the voids increased (**Figure 3**). To further understand the presence of porosity in the surface, a morphological analysis was performed on the samples (**Figures 4d** to **4e**).

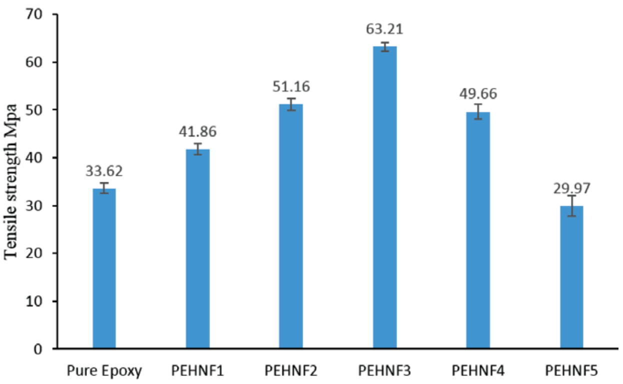

**Figure 5:** Tensile strength of pure epoxy and composites with different weight fractions of alumina-MWCNT hybrid nanofiller

### 3.2 Mechanical property analysis

The integration of alumina-MWCNT nanofillers into the epoxy matrix significantly improved the pure-epoxy properties. Five specimens were tested under same environment condition and the average results were plotted (**Figure 5**). It was found that the epoxy hybrid nanocomposites exhibited a considerable improvement in the tensile strength compared with pure epoxy. 0.1 *w*/%, 0.2 *w*/% and 0.3 *w*/% hybrid nanofillers added to pure epoxy caused 26 %, 52 % and 88 % improvements in the tensile strength, respectively. Furthermore, the 0.4 *w*/% hybrid nanocomposite exhibited an improvement value of 47 % compared with pure epoxy, but also a decrease in the tensile strength when compared with the 0.3 *w*/% specimen. In fact, alumina-MWCNT hybrid nanocomposites brought a strong reinforcement to the epoxy composite, helping to absorb the load and prevent a sudden fracture. Moreover, the 0.3 *w*/% nanofiller hybrid nanocomposite significantly improved the load absorbing capacity due to the homogeneous dispersion in the matrix and caused the predominant mechanical interlocking. Therefore, the 0.3 *w*/% alumina-MWCNT hybrid nanfiller interface exhibits good mechanical properties.

To understand the hybrid nanocomposite effect on the interlocking mechanism, fractured surfaces of the specimens were subjected to a morphology analysis. A

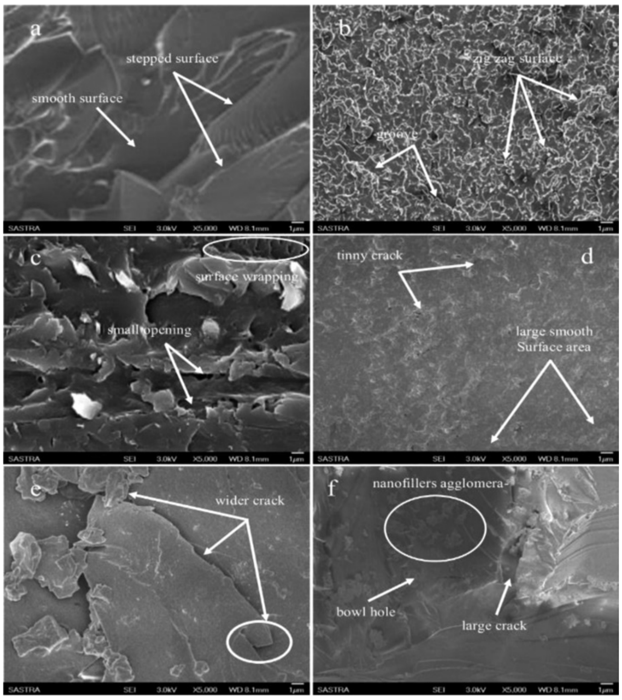

**Figure 6:** SEM morphology analysis of: a) pure epoxy, b) PEHNF1, c) PEHNF2, d) PEHNF3, e) PEHNF4, f) PEHNF5

smooth, glossy surface with a stepped morphology was observed for the epoxy by FESEM. The pure-epoxy fractured surface is brittle (**Figure 6a**). The morphology analysis revealed that different cracks were induced into the hybrid nanocomposites. The cracks were characterized based on the size of their openings and propagation. The PEHNF1 hybrid nanocomposite exhibits small groove cracks along with a zig zag surface, resulting in hybrid nanocomposite reinforcement, which improved the epoxy properties and changed the brittle phase into a partially ductile one (**Figure 6b**). Furthermore, the PEHNF2 hybrid nanocomposite fracture surface exhibits cracks with small openings and a wrapping morphology is observed. During the crack initiation and propagation, the load carrying capacity is likely to be improved due to the impact on the reinforcement. Further crack initiation and propagation are also restricted by the reinforcement elements (**Figure 6c**). Similarly, the PEHNF3 hybrid nanocomposite fracture surface exhibits smooth and tinny cracks, resulting in a homogeneous distribution and good interlocking mechanism that significantly improve the epoxy properties and load carrying capacity. Further, the formation of waves, like an extended surface, shows the elastic nature of the composite, which significantly increased the load carrying capacity; tinny cracks and good interlocking of the composite are observed (**Figure 6d**).

The PEHNF4 hybrid nanocomposite morphology analysis revealed wider cracks on the fracture surface due to the nonhomogeneous dispersion of the reinforcement due to the excessive addition of the hybrid nanofiller (**Figure 6e**). The crack phenomenon and structure are considerably good when compared with pure epoxy, but showing a reduced load carrying capacity when compared with the PEHNF3 composite. Further addition of the hybrid nanofiller (PEHNF5 – 0.5 *w*/%) to pure epoxy exhibits a lower performance than pure epoxy. A large quantity of the hybrid nanofiller forms into a bundle due to the van der Walls force so that no homogenous distribution is achieved and the fracture surface morphology exhibits large cracks and bowl holes while nanofiller agglomeration also indicates the excessive addition of the nanofiller (**Figure 6f**). Obviously, the typical crack initiation and propagation were the fundamental factors that caused the failure of the hybrid nanocomposite specimen. The reinforcement of the alumina-MWCNT hybrid nanofiller added to pure epoxy significantly improved the load carrying capacity, and the fracture surface morphology indicates that the interface between the hybrid nanofiller and the epoxy was significant, improving the mechanical properties. Compared with pure epoxy, the load carrying capacity is improved up to the addition of 0.3 *w*/% of the hybrid reinforcement. It is suggested that the interface bonding strength is increased significantly. However, no noticeable change in the mechanical properties is observed with the 0.4 *w*/% and 0.5 *w*/% hybrid reinforcements due to the saturation level of the reinforcement and agglomeration formation. According to this research, an excessive addition of nanofillers leads to a change in the matrix material natural properties; the 0.5 *w*/% nanofiller composite also exhibits a poorer performance than pure epoxy.

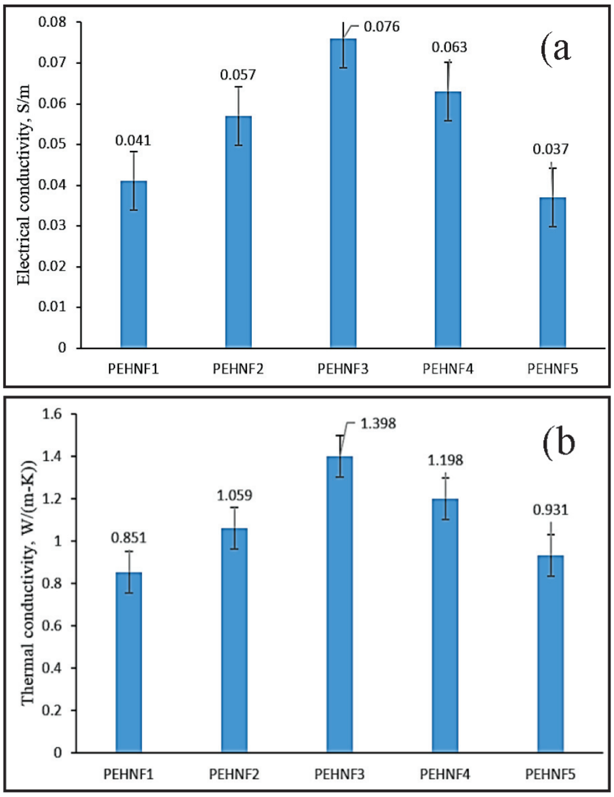

**Figure 7:** a) Electrical conductivity, b) thermal conductivity of pure epoxy and nanocomposites with different nanofiller weight fractions

### *3.3 Electrical and thermal conductivity of hybrid nanocomposites*

Investigations were made into the electrical conductivity (Equation 2) of the reinforced hybrid nanocomposites as shown in **Figure 7a**. The electrical conductivity of the alumina-MWCNT hybrid nanocomposites with filler weight percentages of (0.1, 0.2, 0.3, 0.4 and 0.5) *w*/% is (0.041, 0.057, 0.076, 0.063 and 0.037) S/m, respectively. Due to the uniform distribution of nanofillers and the interlocking mechanism, the electrical conductivity of the hybrid nanocomposite significantly increased by 85 % with the 0.3 *w*/% filler addition. Furthermore, the epoxy matrix agglomeration and discontinuity caused the electrical conductivity of the 0.4 *w*/% and 0.5 *w*/% nanofiller composites to decrease significantly. **Figure 7b** displays the thermal conductivity of the composites. It was discovered (Equation 3) that when compared to the other nanocomposites, the hybrid nanocomposite with the 0.3 *w*/% filler addition has its thermal conductivity improved by 64 %. This outcome shows how an ideal reinforcement of the hybrid nanocomposite enhances the underlying material characteristics.

## 4 CONCLUSIONS

In conclusion, by comprehending the mechanical properties of composites, it is possible to predict a product performance more correctly. The considered nanofiller-reinforced polymer nanocomposites have higher or lower degrees of interior voids due the distribution of particles. Structural properties greatly affect the performance due the presence of voids, the so-called defects or one of the weaknesses of nanocomposites. In an effort to eliminate the voids during the sample preparation, more attention was devoted to the sonication process. Pure epoxy and alumina-MWCNT hybrid nanofiller reinforced nanocomposites were successfully prepared. The 0.3 *w*/% filler nanocomposite exhibited an increase in the tensile strength of 88 % when compared to pure epoxy. Both the interfacial adhesion and mechanical interlocking mechanism were greatly improved by adding the right weight fraction of alumina-MWCNT hybrid nanofiller to pure epoxy. Furthermore, the reinforcement of hybrid nanocomposites can increase the load carrying capacity, which leads to a ductile failure and results in an enhancement of the tensile strength. Similarly, the electrical and thermal conductivity of the 0.3 *w*/% nanofiller nanocomposite significantly improved, by 85 % and 64 %, due to the homogeneous distribution of the nanofiller in the host matrix. Considering different weight fractions of alumina-MWCNTs, additions of the hybrid nanofiller up to 0.3 *w*/% lead to a considerable improvement in all aspects. Further additions of the hybrid nanofiller, 0.4 *w*/% and 0.5 *w*/%, exhibit considerable reductions in the results due to the saturation level of the matrix. The FESEM morphology analysis helped us understand the fracture surfaces of the hybrid nanocomposites. This research work was focused more thoroughly on the mechanical properties as well as electrical and thermal conductivity of the reinforced epoxy nanocomposites. The wear and erosion characteristics are associated with the proposed models, and our findings can provide an insight into the development of new composites for engineering applications.

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