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Research Article

Effect of Different Dielectric and Magnetic Nanoparticles on the Electrical, Mechanical, and Thermal Properties of Unidirectional Carbon Fiber-Reinforced Composites

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Carbon fiber-reinforced particulate composites are immensely used in commercial and military applications due to their excellent functional and mechanical performance. Several studies have been reported to use nanofiller in carbon fiber-reinforced composites to improve their functional and mechanical performance. However, a comparative study was required to depict the best dielectric and magnetic nanofillers with excellent functional and mechanical performance. The current research was performed to compare the effect of different dielectric and magnetic nanoparticles on the electrical, mechanical, and thermal properties of carbon fiber-reinforced composites. The objective was to identify a nanofiller with excellent electrical, mechanical, and thermal properties with the same weight ratio and a potential candidate for EMI shielding application. Unidirectional composite prepregs containing 2% (by weight) of each magnetic and dielectric nanofillers were fabricated on an in-house developed lab-scale UD prepreg manufacturing setup. Among the dielectric nanofillers, the composite samples containing MWCNT nanofiller showed the highest electrical, thermal, and mechanical properties. The composite samples containing titanium oxide nanofillers showed better flexural, electrical, and thermal properties among magnetic nanofillers.

1. Introduction

Carbon fiber-reinforced particulate composites are trending due to their extraordinary characteristics such as lightweight, excellent mechanical, thermal, and electrical properties [1]. Different properties of fiber-reinforced composites can be augmented with the addition of suitable nanofillers in suitable quantities. There is a limit at which a particular property is abruptly changed, and this limit is called the percolation threshold. The percolation threshold is different for different materials and properties. Below this percolation threshold, the material does not significantly affect the nanocomposite's electrical, mechanical, and thermal properties [2]. The minimum percolation limit is the material's intrinsic property and depends upon the type of material and its density [3]. The density of a material is also a percolation limit defining factor. At the same weight ratio and particle size of nanofillers, the nanofiller with higher density will have fewer nanoparticles, while the nanofillers with lower density will have more nanoparticles [4]. So, the lower density material will have a lower percolation limit due to the higher number of nanoparticles. The higher density material will have a higher percolation limit due to the lower number of nanoparticles.

The materials' intrinsic properties and aspect ratio also significantly affect nanocomposites' mechanical, thermal, and electrical properties [5]. Mechanical and thermal properties also depend upon the interfacial interaction between matrix and nanofiller [6]. The stronger the interfacial interaction, the higher will be thermal and mechanical properties. Epoxy resin has exhibited excellent interfacial interaction with many nanofillers [6, 7]. However, pure epoxy is an

Table 1: Comparison of electrical and thermal properties of CFRC.

Sr.	Nanofiller	Filler's ratio (%)	Electrical conductivity (S/cm)	Thermal conductivity (W/mK)	Reference
1	MnO_2	12	4.2×10^{-4}		[25]
2	MWCNTs	7	1×10^{-2}		[1]
3	CNTs	3	1×10^{-4}	0.65	[17]
4	MWCNTs	1.5	10^5 ohm/cm	0.75	[20]
5	MWCNTs	0.5	1×10^{-5} to $1 \times 10^{-12*}$		[5]
6	MWCNTs	3		0.30	[15]
7	Graphene NP	3		0.45	[15]
8	MWCNTs	10	1×10^1		[4]
9	Graphene NP	10	9×10^{-1}		[4]

*Depending upon aspect ratio.

insulator of electric current and has a very low electrical conductivity (~10^{-15} S/cm) [8]. Pure carbon fiber is a conductor of electric current, and its conductivity is reduced with the addition of epoxy resin to form a composite structure. The electrical conductivity of carbon fiber-reinforced composites (CFRCs) can be enhanced by adding suitable nanofillers [9]. The electrical and thermal conductivity properties of nanofillers depend upon various factors such as size and type of material, dispersion technique, filler ratio, aspect ratio, surface smoothness, and intrinsic crystallinity of filler structure [10].

Among all these factors, the aspect and filler ratios are paramount for improving composites' electrical conductivity. The higher the aspect and filler ratio, the higher will be the electrical conductivity [2]. The filler-matrix interface is also an essential factor that affects composite thermal conductivity and mechanical performance [3]. The thermal conductivity of the composite structures increases with increasing the ratio of nanofillers and the specific measuring temperature [11]. Pure epoxy resin also has low thermal conductivity. The thermal conductivity of the epoxy-based composites can be improved by adding suitable nanofillers with high thermal conductivity [12, 13]. Acoustic phonons are responsible for heat transfer in polymer composites. The number of acoustic phonons is directly linked with the ratio of nanofillers. The ambient temperature also influences electrical and thermal properties. After a particular temperature point, a sharp increase in electrical resistivity is referred to as a positive temperature coefficient of resistivity [14].

Many researchers [10, 15–19] have reported that adding MWCNTs to the matrix-based composites improves the electrical, mechanical, and thermal properties. Duan et al. [20] studied the combined effect of graphene and MWCNTs on electrical and thermal conductivity. They found that there is a relatively low percolation threshold of combined materials as compared to individuals. The addition of both fillers significantly improved electrical, mechanical, and thermal properties [21]. The electrical and thermal properties of graphene nanocomposites were better than the MWCNTs nanocomposites, while MWCNT nanocomposites showed better mechanical properties than graphene-based nanocomposites.

Graphene and titanium dioxide are good candidates for applying EMI shielding and improving electrical, thermal, and mechanical properties [22, 23]. Smaller dimensions of graphene sheets significantly improve fracture toughness compared with large ones. Because of the stress concentration factor, crack generation and propagation is higher in large dimensional sheets [24].

Despite this, various studies have been reported on the effect of different nanofillers on different functional properties of composites, shown in Table 1. There is a lack of a comprehensive comparative study on the effect of various magnetic and dielectric nanofillers on the mechanical, electrical, and thermal properties of unidirectional (UD) carbon fiber-reinforced nanocomposites. This study is aimed at comparing the effect of different magnetic and dielectric nanofillers on the electrical, thermal, and mechanical properties of UD carbon fiber-reinforced composites, which may be a potential candidate for EMI shielding applications well. A dedicated lab-scale unidirectional prepreg composite manufacturing setup was developed, cross-ply laminated composite plates having four plies were fabricated, and testing of the composite laminates was performed as per standard test methods.

2. Experimental

2.1. Material. Carbon fiber tow (T-800), with twelve thousand filaments (12 K), was procured from Zhongfu Shenying Carbon Fiber China as reinforcement material. The aerospace-grade epoxy resin (Araldite LY 564) and the hardener Aradur 22962 imported from Huntsman International LLC, USA, were used as matrix materials. The weight ratio of epoxy resin to hardener was 4 : 1, which was maintained for all composite samples. The specifications of dielectric and magnetic nanomaterials used as fillers are given in Table 2. These specifications were provided by the manufacturers of nanofillers and used as received without any modification or pretreatment.

Table 2: Specifications of different dielectric and magnetic materials.

Material name	Codes	Particle size (nm)	Density (g/cm^3)	Manufacturer/supplier
Multiwalled carbon nanotubes	A	10-30	2.25	Hwnano (China)
Silicon carbide nanoparticles	B	50-70	3.32	Nanografi Nanotechnology (Turkey)
Graphene nanoparticles	C	10-30	0.014	The Sixth Element, Inc (China)
Carbon black	D	30-45	0.28-.3	Xfnano (China)
Manganese dioxide	E	15-45	4.0	Nanografi Nanotechnology (Turkey)
Titanium dioxide	F	30-50	4.23	Hwnano (China)
Cobalt oxide	G	50-100	8.92	Nanografi Nanotechnology (Turkey)
Nickel oxide	H	20-30	6.67	Hwnano (China)
Zinc oxide	I	25-50	5.61	Jinda NanoTech. (China)
Ferric oxide	J	100-200	5.24	Hwnano (China)
No particle	Bk	————————	————————	————————

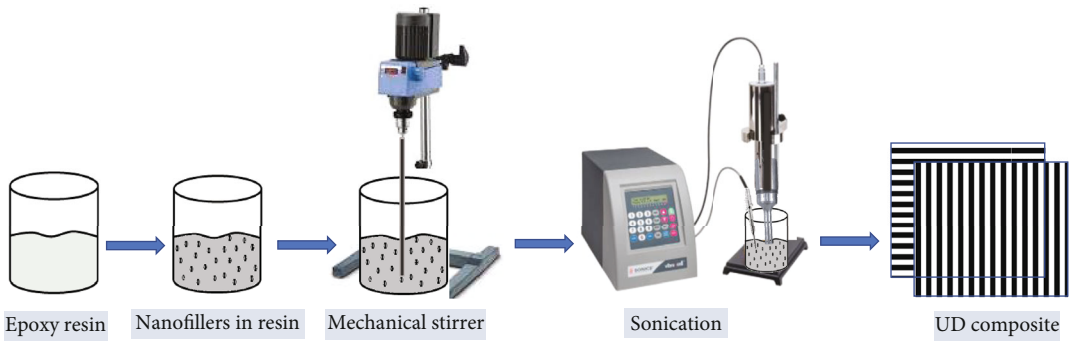

Figure 1: Schematic diagram of dispersion preparation.

2.2. Preparation of Dispersion of Matrix and Nanoparticles. Each nanoparticle's dispersion was prepared independently by adding nanofillers to the matrix material. The ratio of each nanofiller to the matrix was 2% by weight. The nanoparticles were gradually introduced to acetone while being constantly stirred for five minutes to avoid agglomeration. After the addition of epoxy resin, the mixture was mechanically stirred for 15 minutes to obtain uniform dispersions [26]. The obtained dispersion was sonicated in a probe sonicator (SONICS & Material Inc) for 45 minutes at the frequency of 20 kHz ± 50 Hz [27]. The dispersion was mechanically stirred for another five minutes to avoid sedimentation and agglomeration. A schematic diagram of dispersion preparation is shown in Figure 1.

2.3. Fabrication Technique of Carbon Fiber UD Prepreg and Laminated Composites. The prepared dispersion for each nanofillers was poured in the dipping bath of the developed UD composite manufacturing setup separately, as shown in Figure 2. A strand of carbon fiber tow from the cone passes through the dipping bath. The dipping bath containing the dispersion of individual nanoparticles is applied to carbon fibers with the help of dipping rollers. The optimum dispersion quantity is used on carbon fiber while passing through dipping rollers to maintain a uniform fiber volume fraction of 40%. The carbon fiber contains the dispersion of individual nanofiller, and epoxy passes through squeezing rollers. The squeezing rollers remove the extra amount of dispersion, ensuring the uniform application of dispersion on carbon fiber. The impregnated strand of carbon fiber with dispersion is uniformly winded on the surface of the main drum forming one set of prepreg sheets. The given setup developed one sheet of unidirectional carbon fiber prepreg with a thickness of 0.145 mm for each filler sheet. To evaporate the volatile acetone, the sheets were placed in an open environment for two hours at room temperature [27]. Four layers of UD prepreg with the nanoparticle, including the same filling material, were joined according to the stacking sequence [0/90/90/0] illustrated in Figure 3.

Similarly, all the ten sets of composites, comprising one set for each nanofiller, were prepared. One sample was and designed without any nanofiller as a reference sample. These composite sheets were cured in a compression moulding machine according to the curing cycle of the epoxy resin shown in Figure 4. These composites were cured at 80°C for one hour and 200°C for two hours under the pressure of 0.1 N/square foot (0.0107 MPa). The composite samples in the curing chamber were cooled in a natural cooling system till the reduction of temperature to 100°C, maintaining the same pressure in the compression machine. The composite sheet was then taken out from the compression machine and cooled to room temperature.

2.4. Characterization of Nanocomposites. The surface morphology of prepared composite structures was observed using a scanning electron microscope (SEM) test (Cube series, Emcraft). The surface of the composites samples was

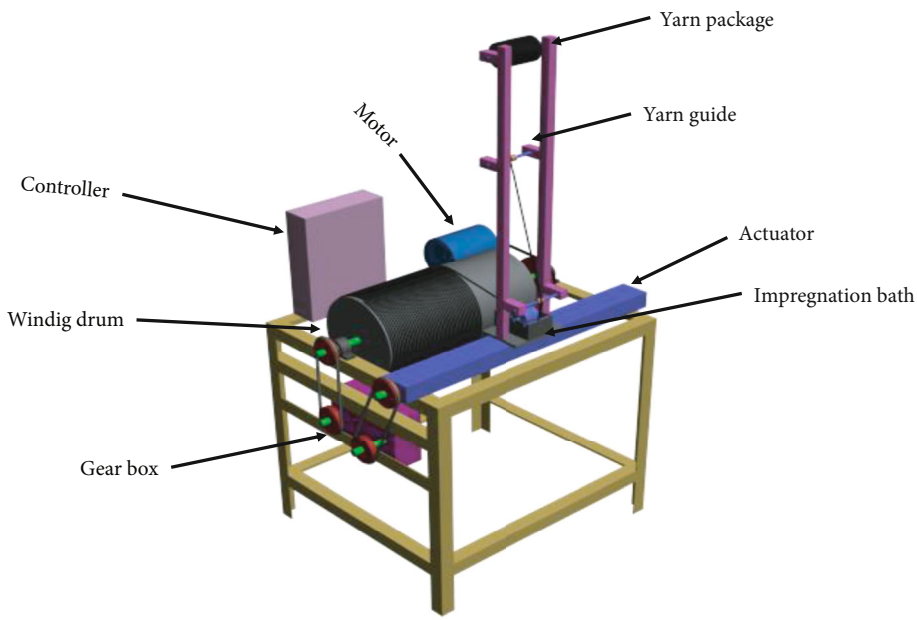

Figure 2: In-house developed lab-scale UD prepreg composite manufacturing setup [28].

(a) (b)

Figure 3: Composite UD samples: (a) single sheet of prepreg and (b) four-ply composite plate after curing.

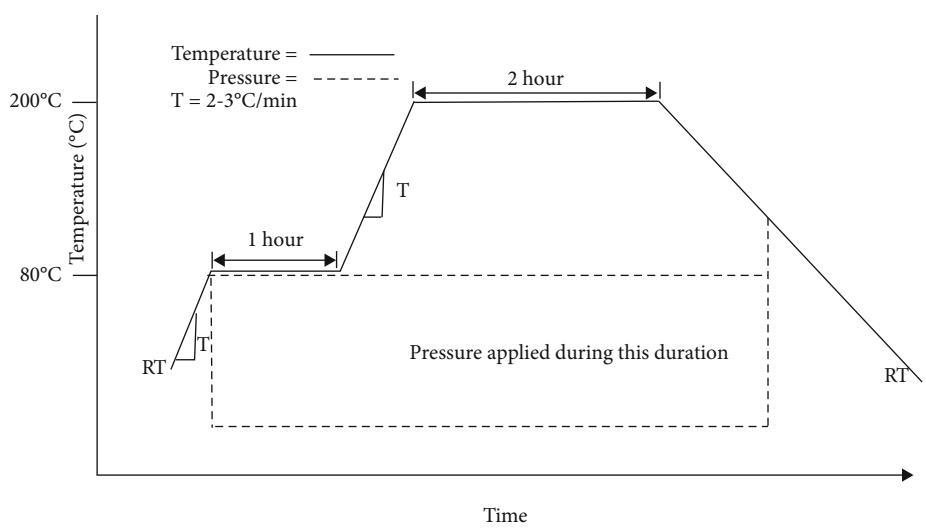

Figure 4: Composite curing cycle from room temperature (RT) to curing and cooling back [29].

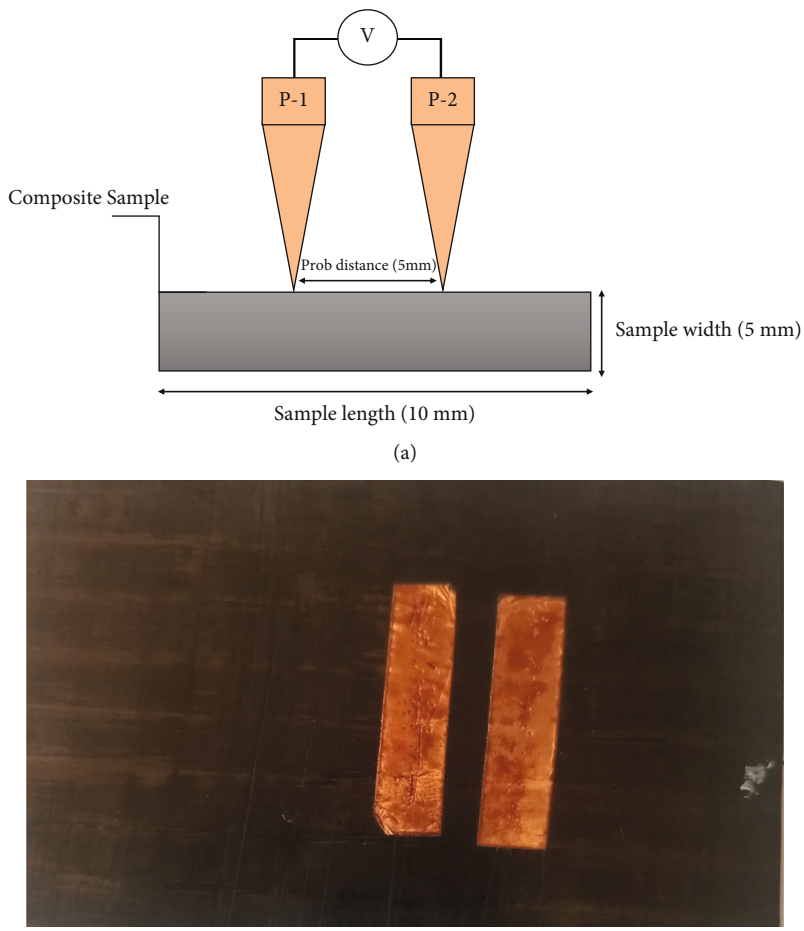

Figure 5: Schematic diagram of (a) two-probe DC conductivity tester and (b) composite sample with copper conducting tape for DC conductivity testing.

gold-coated through sputter coating techniques to facilitate the charge dissipation on the composite surface. The tensile strength of the composite laminates was measured using a universal testing machine (Z100, Zwick/Roell, Germany) with a crosshead speed of 2 mm/min and a gauge length of 120 mm, according to ASTM D-3039. Flexural strength (three-point bending) was measured using the same instrument with a load cell of 100 kN with 1 mm/min crosshead speed. The dimensions of the samples were as per ASTM D-7264 with a span length of 50 mm. According to ASTM D-7136 and ISO-179 testing standards, drop weight and Charpy impact strength were measured. The Charpy impact test was performed with a hammer angle of 148° and hammer energy of 50 J, while the drop weight test was performed with 50 J energy with a striker diameter of 16 mm. Each test has at least three samples run through it.

To measure the electrical resistance of composite samples, first, the sample's surface was prepared using sandpaper of 2000 grit to smooth the surface and remove extra epoxy, as it is electrically insulated. Two conductive tapes were applied on the surface of each composite at the internal distance of 5 mm to improve the accuracy of electrical conductivity, as shown in Figure 5.

The electrical conductivity of the composite sample was measured by two-probe methods using a Keithley electrometer model 2450 source meter. Both probes contact the composite surface at 5 mm from each other. An electrometer was set to measure the current and voltage of the sample. Then, the electrical conductivity was calculated from electrical resistance and resistivity. Thermal conductivity was measured using a thermal conductivity meter DTC300 according to the ASTM E-1530 testing standard. Thermal conductivity was measured at a temperature of 25°C. The diameter of the circular sample was 5 cm, and a silicon paste was applied to the surface to make it smoother for uniform thermal conductivity measurement.

3. Results and Discussion

3.1. Structural Analysis of Developed Composite. The SEM test was performed to check the surface morphology of all developed composite samples. Figure 6, A–J explains the dispersion of nanoparticles in the composite structure. This dispersion of nanoparticles is uniform throughout the surface of composite structures, and there is no significant accumulation of nanoparticles on the surface of composites. The

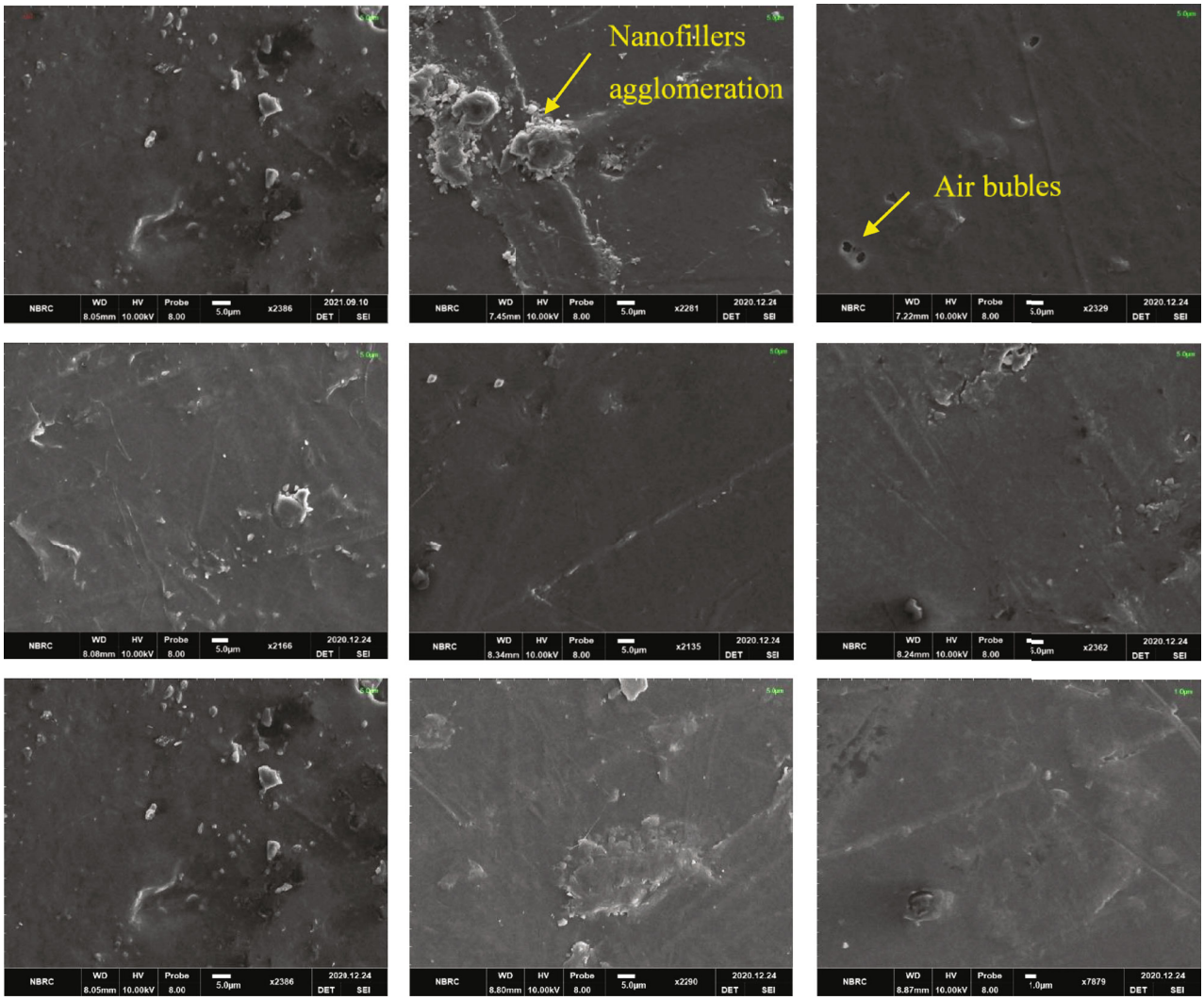

Figure 6: SEM images of carbon fiber/epoxy composites impregnated with nanofillers (A: MWCNTs, B: SiC, C: Gp, D: CB, E: MnO_2, F: TiO_2, G: CoO, H: NiO, I: ZiO, and J: Fe_2O_3).

SEM results also show the smoothness of the surface and voids in the structure. The surface of all samples is uniform, and no holes were present except the sample C, which has a few small voids on its surface. Few agglomerated lumps of nanoparticles were seen on the surface of sample B. The SEM results depict the surface smoothness of advanced prepregs and stacked composites. The surface smoothness elaborates the correlation between nanoparticles and matrix material. The SEM results indicate that the carbon fibers were fully impregnated with dispersion solution, and the dispersion of nanoparticles was uniform in the epoxy resin.

3.2. Electrical Conductivity. The electrical conductivity of unidirectional carbon fiber-reinforced composites, comprising different dielectric and magnetic nanomaterials, is shown in Figure 7. The electrical conductivity of CFRCs with dielectric nanomaterials is higher than those with magnetic materials. Among all the ten samples with different dielectric and magnetic fillers, the composite sample A with MWCNTs shows the highest electrical conductivity value. This value of electrical conductivity of composite sample comprising MWCNTs is almost double that of carbon fiber composite without any nanomaterial. The electrical conductivity of a material depends upon several factors such as the type, density, and atomic structure of the material. MWCNTs show a lower percolation limit than any other nanofillers. Carbon fiber and MWCNTs are electrical conductors, and their composites exhibit high electrical conductivity. Improvement in electrical conductivity is due to the three-dimensional solid conductive network [12] of carbon in the composites and a reduced distance between particles providing the movement to electric charge [20]. Several factors such as aspect ratio, particle size, state of aggregation, uniform dispersion of fillers, homogeneity, and density of conductive fillers affect the conductivity of the nanocomposites. However, in MWCNTs, the length and thickness of nanotubes are also among the key factors controlling electrical conductivity. The longer length and smaller diameter of nanotubes significantly improve the electrical conductivity even at a low aspect ratio [30]. Dielectric SiC (sample B)

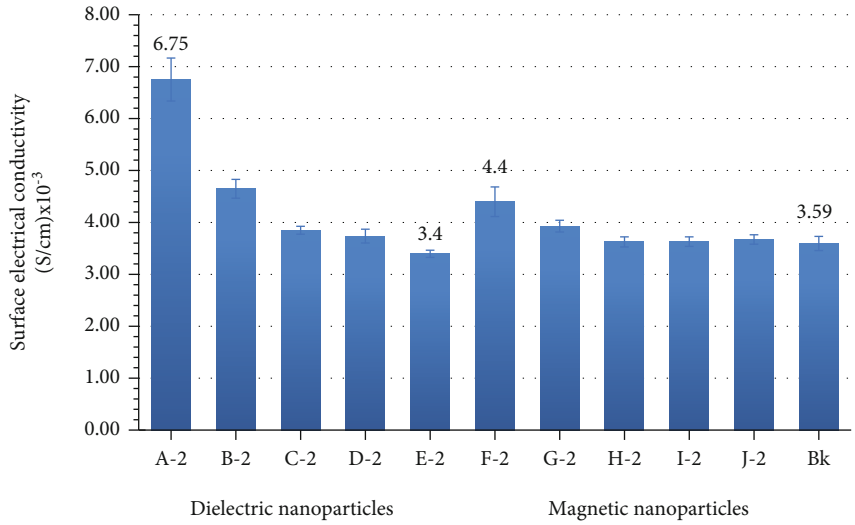

Figure 7: Effect of magnetic and dielectric nanofillers on the surface electrical conductivity of developed composite samples (A: MWCNTs, B: SiC, C: Gp, D: CB, E: MnO_2, F: TiO_2, G: CoO, H: NiO, I: ZiO, J: Fe_2O_3, and Bk: reference sample).

and magnetic TiO_2 nanoparticles (sample F) show the same percolation behaviour and significantly affect the electrical conductivity. Cobalt oxide (sample G) gives electrical conductivity higher than graphene and carbon black despite the high density and lower number of nanoparticles. Cobalt oxide nanoparticles are good candidates for EMI application. The electrical conductivity of nanocomposites with nickel oxide, zinc oxide, manganese oxide, and ferric oxide was not significantly changed. These nanoparticles have a higher density (Table 2). They have less quantity with the same weight ratio and do not attain the percolation limits required for high electrical conductivity.

3.3. Thermal Conductivity. Epoxy-based composites have less thermal conductivity, and their thermal conductivity can be enhanced by adding nanofillers [15]. Heat is transferred in epoxy composites in the form of acoustic phonons [31]. Like electrical conductivity, thermal conductivity is also affected by several factors such as the filler's intrinsic properties, atomic structure, degree of dispersion, measuring temperature, and the distance between the conductive fillers. Thermal conductivity is also a key factor for the IR detection of an object. A composite with a higher thermal conductivity value is not suitable for stealth applications due to its detection by IR light. The addition of nanofillers in nanocomposites provides a thermal bridge that can change the thermal conductivity. If the thermal bridge is thermally a conductor, it effectively enhances the heat flow in the composite. On the other hand, if the thermal bridge is a thermal insulator, it hinders the heat flow and ultimately increases thermal insulation. Figure 8 shows that sample A with MWCNTs has the highest thermal conductivity, and its value increased by around 100% more than the thermal conductivity of reference sample Bk. Because the nanofillers in MWCTNs (sample A) are nanotubes, they form a three-dimensional network of nanofillers in the matrix, facilitating heat dissipation. The carbon nanotubes also cover a large area and provide a conductive network. Their large aspect ratio is dispersed in the matrix without agglomerations, creating an efficient conductive network for phonon diffusion [31].

Thermal conductivity is also the function of the filler ratio. A larger filler ratio promotes thermal conductivity by providing a path to heat flow. Since MWCNTs have low density, a high volume of MWCNTs is used, increasing the number of fillers and providing a conduction path for heat flow. Nickel oxide (sample H) has the lowest thermal conductivity value, even lower than the reference sample (sample Bk). The thermal conductivity of nickel oxide depends upon the crystallinity of the nanostructure and the size of the particles. Large particle size has higher thermal conductivity than smaller particle sizes [32], because in small particle-sized nickel oxide particles, the phonon scattering takes place at the boundaries of particles which causes a reduction in thermal conduction.

3.4. Tensile Properties. Tensile stress-strain curves of the composites impregnated with magnetic and dielectric nanofillers are shown in Figure 9. The effect of both magnetic and dielectric nanofillers on tensile moduli is significant compared with reference sample Bk. The addition of nanofillers in the composite structure improves *Young's modulus* irrespective of the filler's type and properties, as shown in Figure 10(b). This trend is in accordance with the results reported by other researchers [5, 9, 17, 31, 33, 34]. MWCNTs (sample A) show the highest Young's modulus due to higher filler-matrix interaction among the dielectric nanofillers. Young's modulus increased about 74% with the addition of MWCNTs in the composites compared to without any nanofiller. The length and orientation of MWCNTs also play a significant role in improving Young's modulus [10, 35].

The higher the length of the nanotubes, the higher will be Young's modulus. A longer span of nanotubes provides a higher filler-matrix interface, and higher friction significantly enhances Young's modulus. Young's modulus of MWCNTs is even higher than carbon nanoparticles (CNP) [17]. The highest increment in Young's modulus was

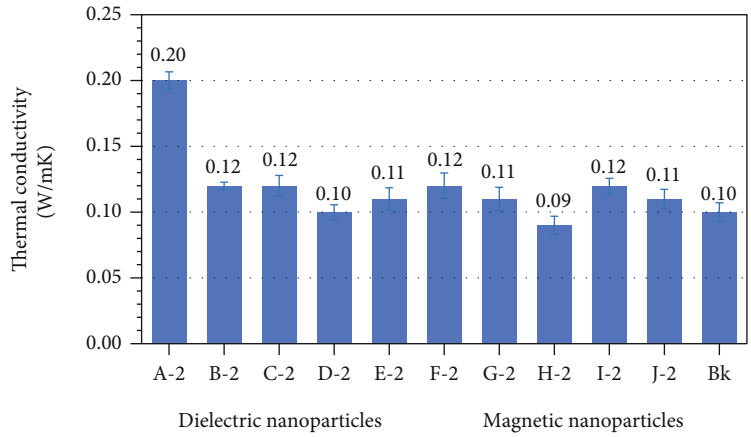

Figure 8: Effect of magnetic and dielectric nanofillers on thermal (A: MWCNTs, B: SiC, C: Gp, D: CB, E: MnO_2, F: TiO_2, G: CoO, H: NiO, I: ZiO, J: Fe_2O_3, and Bk: reference sample).

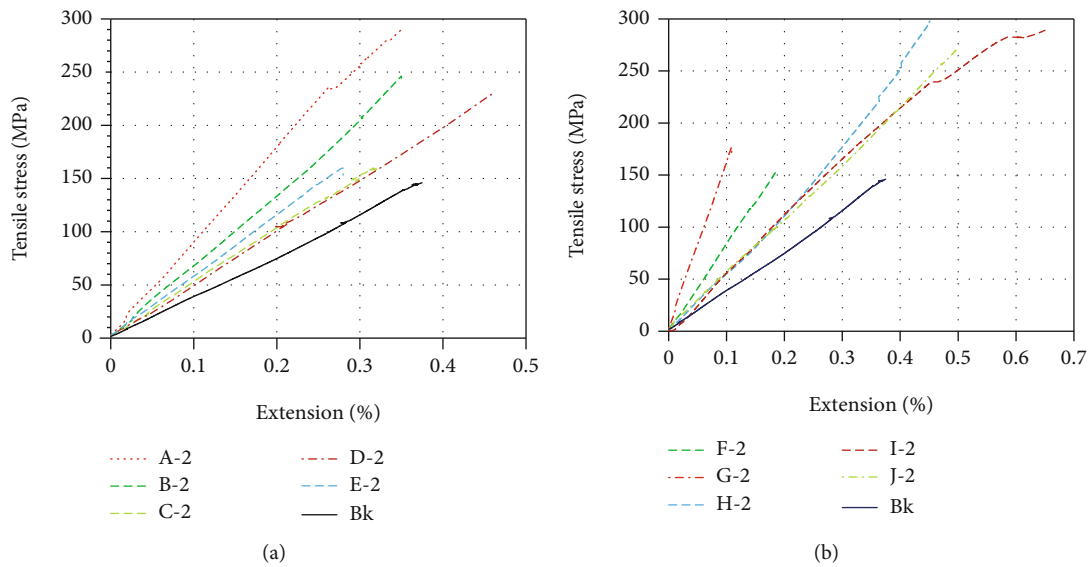

Figure 9: Tensile stress-strain curves for (a) dielectric nanofillers and (b) magnetic (A: MWCNTs, B: SiC, C: Gp, D: CB, E: MnO_2, F: TiO_2, G: CoO, H: NiO, I: ZiO, J: Fe_2O_3, and Bk: reference sample).

observed with cobalt oxide (CoO) (sample G) among all-dielectric and magnetic nanofillers. Young's modulus was improved up to 87% with CoO, which is an extraordinary improvement in Young's modulus. Interfacial adhesion and nanoparticle dispersion are the two main factors that directly influence the mechanical properties of nanocomposites. Load transfer depends upon the interfacial adhesion, which ensures the functionality of composites [23]. A more robust interface between reinforcement and nanofillers results in a better load transfer and improves the mechanical properties. Another factor that significantly affects the mechanical properties is the size of nanoparticles. The smaller the nanoparticles' size, the higher the surface area and the greater the interfacing matrix [34, 36]. The number of particles per unit weight increases by decreasing the particle size, and the distance between particles in the composite also decreases. Higher rigidity and good particle-matrix adhesion make the TiO_2 a good additive for enhancing the mechanical properties. Fabric architecture is also an essential factor that affects the tensile properties of polymer composites. Unidirectional fabric structure has higher tensile properties than biaxial fabric structures due to fewer undulations in unidirectional fabric structures [37, 38]. Both fabric architecture and the concentration of filler can significantly improve the tensile properties of composites.

The effect of magnetic and dielectric nanofillers on tensile strength shown is in Figure 10(a). The tensile strength of CFRCs was improved with nanofillers compared to the reference sample (Bk). The improvement in tensile strength of magnetic materials was higher than in dielectric materials. The highest tensile strength was observed in the NiO and ZnO among magnetic nanofillers and MWCNTs among dielectric nanofillers. Tensile strength depends upon several factors such as filler-matrix interface [39], uniformity of dispersion, filler ratio, type of bonding, nanofiller size, nanofiller's shape, and filler's intrinsic properties. High values of

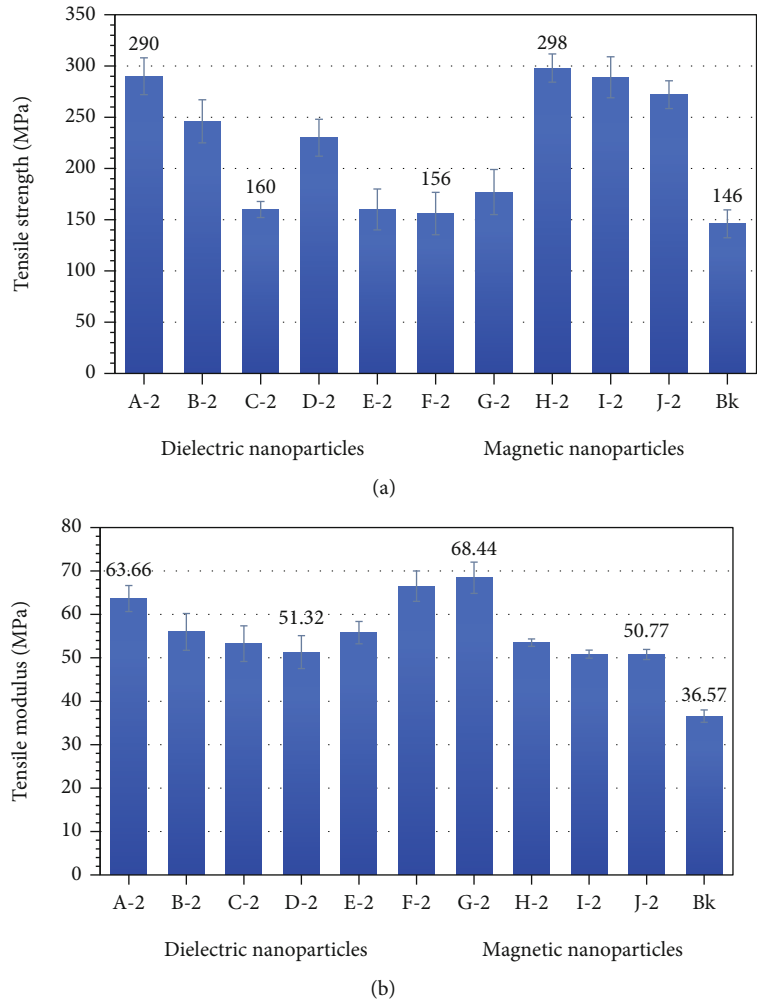

Figure 10: Effect of magnetic and dielectric nanofillers on (a) tensile strength and (b) Young's modulus (A: MWCNTs, B: SiC, C: Gp, D: CB, E: MnO_2, F: TiO_2, G: CoO, H: NiO, I: ZiO, J: Fe_2O_3, and Bk: reference sample).

these factors will significantly enhance the tensile strength of composites structures. The composite structure with MWCNTs nanofiller shows optimum tensile strength values and Young's modulus. The TiO_2 has comparatively high Young's modulus but low tensile strength. Figure 9 shows low strain in the composite, which depicts high modulus in the composites.

3.5. Flexural Properties. Flexural strength demonstrates the stiffness of the nanocomposites. As evident in Figures 11 and 12, incorporating the nanofillers in the composites improves the flexural properties [19]. Sample A with MWCNTs shows the highest flexural strength (Figure 12(a)). The flexural properties were improved by 64.5% with the addition of MWCNTs in the nanocomposites. Just like tensile strength, flexural strength also depends upon the size of the particle, aspect ratio, interfacial adhesion, shape, and dispersion of nanoparticles [15]. The length of nanotubes also plays a vital role in enhancing the flexural strength of nanocomposites. MWCNTs form a 3D network in the internal structure of composites and hinder crack propagation [40].

Composite samples with titanium dioxide (sample F) show a significant improvement in flexural properties. TiO_2 is a good nanofiller that enhances the dielectric, thermal, and mechanical properties. Higher flexural strength and flexural modulus can be attributed to high load transfer and stiffness, providing a crack barrier. Cobalt oxide (sample G) is also an essential nanofiller for improving mechanical properties. Cobalt oxide also shows excellent flexural properties despite the high density and low quantity. The filler-matrix association has a significant effect on mechanical properties.

A good association improves the bonding between nanofiller and matrix and provides resistance to bending. Poor association easily breaks the bonding between the filler and the matrix. The filler is released quickly from the matrix during applied force and provides a moving space. As a result, the stiffness of composites decreases, which results in the reduction of flexural properties. The SiC (sample B) shows such behaviour and exhibits lower flexural strength.

3.6. Charpy Impact Strength. Impact properties are critical for a composite to check its suitability for a particular

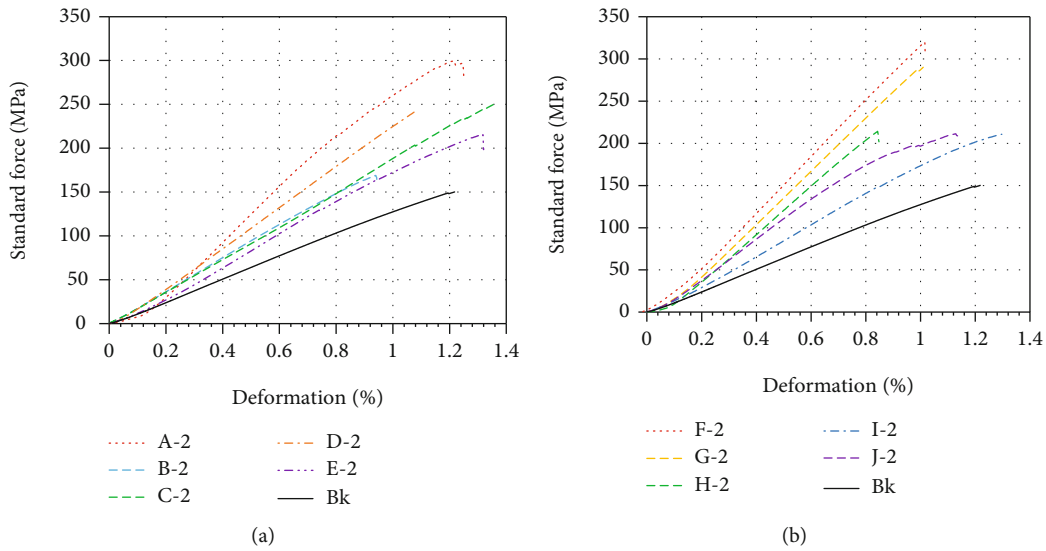

Figure 11: Flexural stress-strain plots of (a) dielectric material and (b) magnetic materials (A: MWCNTs, B: SiC, C: Gp, D: CB, E: MnO_2, F: TiO_2, G: CoO, H: NiO, I: ZiO, J: Fe_2O_3, and Bk: reference sample).

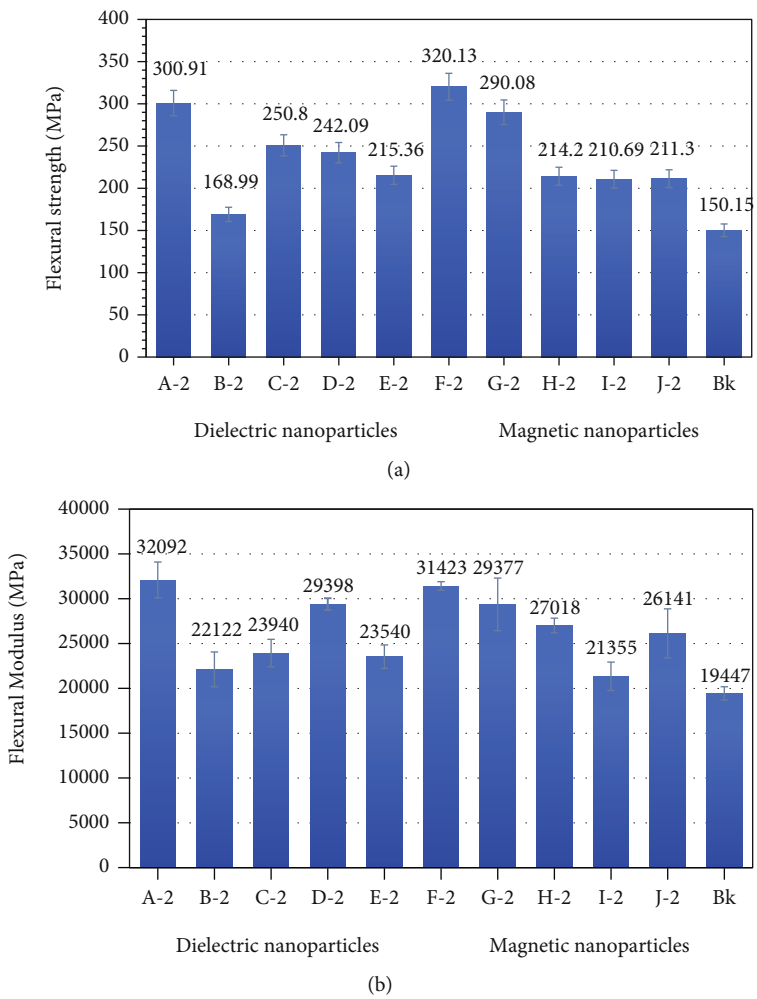

Figure 12: Effect of magnetic and dielectric nanofillers on (a) flexural strength and (b) flexural modulus (A: MWCNTs, B: SiC, C: Gp, D: CB, E: MnO_2, F: TiO_2, G: CoO, H: NiO, I: ZiO, J: Fe_2O_3, and Bk: reference sample).

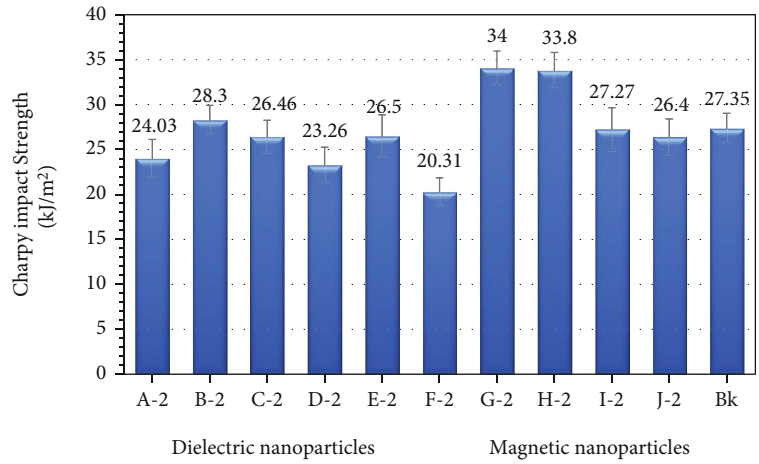

Figure 13: Effect of magnetic and dielectric nanofillers on Charpy impact strength (A: MWCNTs, B: SiC, C: Gp, D: CB, E: MnO_2, F: TiO_2, G: CoO, H: NiO, I: ZiO, J: Fe_2O_3, and Bk: reference sample).

application against impact force [20]. The impact behaviour depends upon the type of reinforcement, filler ratio, and aspect ratio of nanofillers. Impact properties also depend upon the structure of reinforcement [41]. Stitching the UD composites enhances the impact strength by restricting the damaged area. The composite with the longitudinal direction of fibers has the highest impact properties. Impact resistance increases with increasing the filler ratio [35]. Different nanofillers have different impact resistance, as shown in Figure 13.

The impact properties of carbon fiber-reinforced composite structure loaded with different dielectric and magnetic nanofillers are shown in Figure 13. The unnotched testing samples were used because the unnotched samples are considered best for detecting agglomerates, flaws, and initiation of cracks is imperfect [42]. The impact behaviour depends upon the type of reinforcement, filler ratio, and aspect ratio of nanofillers. The impact properties of nanoparticle-loaded composites increase as the loading concentration is increased to a certain point. Then, the impact properties decline as the loading concentration is increased further [35]. The percolation limit is the maximum amount of nanofillers loaded before the impact characteristics deteriorate [20]. This percolation limit is determined by the material's intrinsic qualities and varies from one material to another. Impact properties also depend upon the reinforcement structure [41]. The composite with the longitudinal direction of fibers has the highest impact properties.

The impact properties were improved with cobalt oxide and nickel oxide in the CFRCs and decreased with other nanofillers. Maximum reduction in impact properties was observed by TiO_2, which shows a -25% reduction in its impact properties. This verifies the results cited in the literature [23] that TiO_2 has a percolation loading limit of 2%. The reduction in impact properties of other nanofillers shows that they have lower percolation than 2% of loading concentration. The percolation limit depends upon the material's nature and the density of nanofillers. Table 2 shows that cobalt and nickel oxide have the highest density among all-dielectric and magnetic nanofillers. The materials with high density have low volume per unit weight and have a lower number of nanofillers. The lower number of nanofillers increases the percolation limit of that material. The materials having low density have a higher number of nanofillers per unit weight of the material. More particles, the higher the number of particles, the higher the accumulation of nanofillers in materials structure, which will act as the crack initiator leading to failure of the composite structure [23]. The material's properties in Table 2 and impact properties in Figure 13 support each other. Besides the density of a material, the filler matrix interface is also an essential factor that affects the impact properties. Strong bonding between nanofillers and matrix reduces the voids and expansion of cracks, improving impact properties [43].

4. Conclusion

The effect of different magnetic and dielectric nanofillers on carbon fiber composites' electrical, thermal, and mechanical properties was studied. Among dielectric nanoparticles, the composites with MWCNT nanofiller show better electrical conductivity and thermal conductivity. A 3D network of nanotubes is developed, which facilitates the conduction of electric charge and flow of heat. The mechanical properties such as tensile strength, tensile modulus, flexural strength, flexural modulus, and drop weight impact of composites with MWCNTs were also significantly improved, showing a lower percolation limit MWCNTs than other nanofillers. The 3D network also improves the flexural strength and hinders the propagation of cracks. Among magnetic nanoparticles, titanium oxide (sample F) shows better electrical and thermal properties than other magnetic nanofillers. The titanium oxide (sample F) also shows better flexural strength and modulus, but tensile strength, modulus, and drop weight impact properties were better for nickel oxide (sample H), cobalt oxide (sample G), and zinc oxide (sample I), respectively. Impact properties depend upon the stiffness of composites. The nanocomposite with a robust particle-

matrix interface makes the composite stiff and has high impact resistance. To attain higher electrical, thermal, and mechanical properties, a hybrid composite of MWCNTs and TiO_2 will be suggested, significantly improving the mentioned properties.

Data Availability

The data will be provided on requirement.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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