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Dispersion mechanism of nanoparticles and its role on mechanical, thermal and electrical properties of epoxy nanocomposites - A Review

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Abstract

The combined effect of nano-reinforcements on the mechanical performance of nanocomposites, which are a novel class of epoxy matrix hybrid nanocomposites containing multiwall carbon nanotubes (MWCNT), graphene, and nanodiamonds (NDs), is drawing substantial attention from many research communities. The discussion concentrates on the dispersion techniques adopted for the preparation of epoxy composites containing different types of nanoparticles (3-D fillers, nanofibers, nanotubes, and plate-like fillers). This review paper covers the electrical, thermal, and mechanical properties of carbon nanotubes (CNTs), graphene, and nanodiamond-reinforced epoxy nanocomposites and correlates them with the topographical features, morphology, weight fraction, dispersion state, and surface functionalization of CNTs, graphene, and nanodiamond. This review paper also summarises recent developments in the dispersion method of different carbon nanoparticles in epoxy matrix.

1. Introduction

In the last two decades, there have been many developments in the field of composite materials using different CNTs, graphene, and nanodiamonds. Now a days, there are many emerging applications where dispersion of nanoparticles plays important role into different polymer matrixes to achieve the optimum performance. The various properties of the nano-composite material, such as strength, hardness, thermal conductivity, conductivity, wear properties, optical properties, etc., are directly improved or enhanced by the distribution of particles. The interactions between nanoparticles and matrix depend on the nature of dispersion technique. Since nanoparticles have a higher surface to volume ratio, their interactions with the epoxy matrix are more intense. A well dispersed technique generally yields more desirable composite properties. The inorgaic fillers are frequently required to enhance the mechanical properties of epoxy resin, which results in the development of epoxy composites or nanocomposites [1,2].

The different aspect of dispersion of nanodiamonds and other carbon nanofillers such as graphene and CNT nanoparticles with their exceptional physical properties are still not reported. NDs is a member of the carbon family, and due to its excellent mechanical and structural integrity (small average diameters of 5 nm, large and accessible surface areas (300 $m^2 \cdot g^{-1}$ to 500 $m^2 \cdot g^{-1}$)), and rich, adaptable surface chemistry make NDs a strong candidate for use as the final polymer matrix reinforcement material [3]. Recent research has demonstrated that an air oxidation technique significantly improves the purity of NDs powders, enabling control of the NDs surface chemistry, sp^2 to sp^3 carbon ratio, and crystallite size [4]. Detonation nanodiamond (DND) with sp^3 carbon-carbon bond is one of the most promising candidates for constructing extremely strong nanocomposites among them [5]. Due to their large specific surface area, strong adherence of the nano-filler matrix, and exceptional mechanical capabilities of the planar sp^2 carbon bonding network in graphene, these nano-composites have a great potential for improving mechanical qualities [6-8].

This article addresses the various dispersion techniques during the fabrication of nanocomposites based on the three kinds of reinforcing materials: nanodiamonds, graphene, and MWCNT. It also reviews the physical phenomena of dispersion and the relationship between dispersion and physical qualities.

2. Physical phenomenon

Nanotechnology and nanoscience have emerged as the fastest growing fields for research and have attracted many researchers for their extensive study. They have developed many applications for large and small things and can be used across all the other science fields, such as chemistry, biology, physics, materials science, and engineering. These materials have a length scale below 100 nm and are often compared to human hair, which is about 80,000 nm wide. The nanomaterials, compared to the same mass of materials, have

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a relatively large surface area. Therefore, the material's high chemical reactivity (and in some cases, the most inert materials react when manufactured at the nanoscale) affects its overall properties, including its mechanical, thermal, electrical, and rheological properties. The overall bulk properties of materials usually change rapidly with the nano-ingredients. Nanostructure has special properties that are exclusively due to its nanoscale proportions. The number of dimensions of the material exceeds the nm range (<100 nm) and shows various dimensional characters. Figure 1 shows the different types of nanostructured materials.

3. Dispersion mechanism and the evaluation techniques

The structural heterogeneity of polymers and their phase separation on a nanoscale have recently been studied using a variety of experimental approaches and methodologies based on mathematical or statistical assumptions. There have been numerous studies that have examined how dispersion and the process of dispersion directly impact the physical properties, and these studies have all been described in recent papers. Figure 2 shows the influence of molecular surface modification on the dispersion of nanoparticles in an epoxy matrix. The various mechanical, thermal, and rheological properties depend on the degree of dispersion. The effective dispersion techniques improve the chemical bond formation between the epoxy matrix and the reinforcement particle. Hence, the bond interaction between the epoxy matrix and the reinforced nanoparticles has been improved. Due to the improved nanoparticles–epoxy matrix interaction, the mechanical, thermal, and electrical properties of epoxy composites were enhanced. There are so many other parameters that influence the properties of composites, like shape, size, and amount of filler.

Transmission electron microscopy (TEM) and Scanning electron microscopy (SEM) are the two-characterization technique most frequently employed for dispersion valuation. The foremost efficacy of this TEM methodology is for the quantification of exfoliated or intercalated samples. The NDs particles were disentangled from the entanglements and uniformly mixed in the epoxy matrix, with varying NDs concentrations in the hardened epoxy matrix, as shown in Figure 3.

4. Influence of epoxy system on the mechanical and physical properties of nanocomposite as a matrix materials

The outstanding mechanical characteristics, thermal stability, solvent resistance, and production simplicity of epoxy-based composite materials make them very popular [9,10]. Epoxy and its nanocomposites are used in a variety of industries, such as aerospace, automotive, marine, sports equipment, building, structure, electrical, and electronic systems, biomedical devices, thermal management systems, adhesives, paints, and coatings [11]. The fundamental disadvantage of epoxy resins for structural applications may be their innate brittleness. Epoxy materials, however, have a variety of engineering uses that are frequently constrained by their brittleness and poor electrical and thermal properties [12-14]. The molecular structure of the epoxy matrix can be changed by compatible fillers can be added as a quick fix for this issue. The inorganic nanofillers have been shown to be a highly effective strategy for improving material performance [15,16].

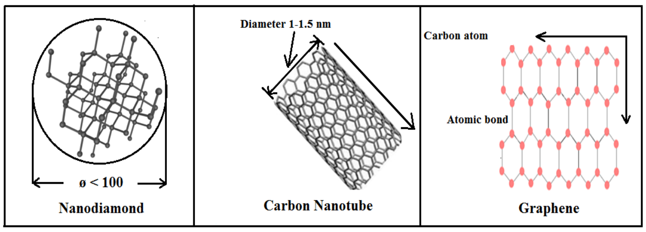

Figure 1. Different nano-structures of materials.

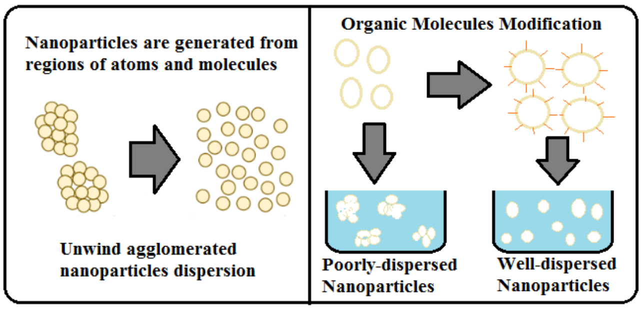

Figure 2. The schematic approach to improve the dispersion by surface modification.

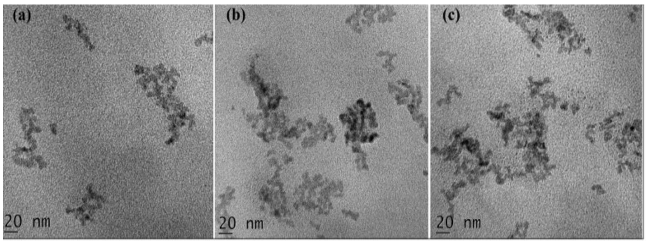

Figure 3. TEM images show the dispersion of the NDs with cured epoxy matrix at different concentration

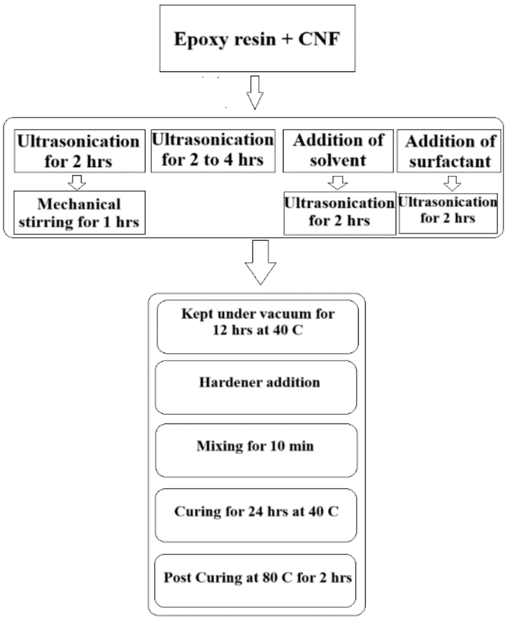

Figure 4. Flow chart of dispersion procedures of carbonaceous particles in epoxy composite.

Combining carbonaceous nano-materials with epoxy matrix materials improves composite properties and fabrication of composites. Depending on the specific properties and subsequent application, the appropriate particles will either be in 0-D, 1-D, or 2-D form. The properties of composites depend on the mixing technique and the state of preparation of the mixture. Therefore, it's important to note any issues or challenges with compounding. Three basic carbon particles such as CNTs, graphene, and NDs need extra attention due to their popularity. The detailed dispersion procedures of carbonaceous particles in epoxy composites are given below in Figure 4.

5. Influence of CNTs on various mechanical properties of epoxy nanocomposites

The primary issues and difficult tasks in the development of high-performance CNT/epoxy composites are to achieve a good dispersion state, good alignment, and strong interface bonding of CNTs in the epoxy matrix, form a structural frame, and achieve a good load transfer medium from the matrix to the CNTs during the loading condition. Effective epoxy composite reinforcements require adequate CNT dispersion and strong interfacial bonds between the epoxy matrix and CNTs [22]. Since their discovery, single and MWCNTs have proven to have an excellent blend of thermal, electrical, and mechanical capabilities thanks to experimental results and theoretical expectations [17].

To maximise CNTs' potential as efficient reinforcements in high-strength composites, they must not form aggregates and be evenly disseminated to minimise slippage. As a result of the inner layers slipping because of the comparatively weak Van der Waals bonding between the concentric layers, the material's capacity to support loads may be reduced [18]. The dispersion of CNTs in epoxy matrices can be improved by a variety of methods, including chemical functionalization, in situ polymerization, and physical blending. To boost the CNTs' dispersants in the epoxy matrix, surfactant is utilised. Utilizing functionalized MWCNTs instead of pristine MWCNTs significantly improved the dispersion and alignment of MWCNTs [23].

The chemical functionalization's are the most common methods to improve the nanomaterials dispersion in the epoxy matrix nanocomposites. There have been several research articles reporting that after passing through chemical modification, CNTs can be improve their solubility and transform themselves into convenient materials. The chemical functionalization of nanoparticles is achieved in two ways: by covalent interactions and by non-covalent interactions. Non-covalent functionalization of CNTs has been done by melamine, which is an effective method for preventing agglomeration of CNTs mixed uniformly in the epoxy matrix [24]. CNTs and epoxy resins can be directly combined through blending using high shear or ultrasonic forces [20]. The disadvantage of blending is that CNTs cannot be efficiently dispersed in epoxy resins. Furthermore, the amount of CNTs is limited due to the high viscosity of the epoxy resin. In order to achieve better CNT dispersion in epoxy resins, solution mixing is the most used technique [21]. In this process, mechanical magnetic agitation, stirring, or high-energy sonication are typically used to drive the dispersion and mixing of CNTs and epoxy in a suitable solvent. This is followed by carefully regulated solvent evaporation. For the dispersion of CNTs in epoxy resins, there are numerous methods, such as solution mixing, blending, and large-scale processing.

As a result, extensive research studies have been focused on the CNT nanofiller reinforcement of epoxy matrices. CNTs' size, helicity, or chirality all affects their physico-mechanical characteristics. Composites made of nanotubes and polymers exhibit poorer than expected physical and mechanical properties. For examples, the tensile modulus of epoxy/CNT composites was only increased from 3.1 GPa to 3.71 GPa with 5 wt% MWCNT [19]. Ajayan *et al.* fabricated and studied the properties of CNT based epoxy matrix nanocomposites [87]. The major challenges are initiating with a high quantity of CNTs with regulated alignment and uniform dispersion throughout the polymer matrix and improving the interface characteristics for the epoxy/CNT composites to achieve optimal properties. Table 1 shows the dispersion techniques reported by different researchers and their influence on various properties of CNT-reinforced epoxy nanocomposites.

Table 1. Different dispersion methods of CNTs with epoxy and the properties enhancement.

Type of solvent	Type of fillers	Dispersion method	% Enhancement	Ref.
-	MWCNT	Bath sonic	Tensile strength 26%	[25]
-	f-MWCNT	Planetary centrifugal mixer	Tensile strength 22% Young's modulus 64% Fracture toughness100%	[26]
Acetone	MWCNT	Bath sonic + Mechanical stirrer	Tensile strength 34% Young's modulus 41%	[27]
-	f-MWCNT	Bath sonic	Tensile strength 57% Young's modulus 40%	[28]
Acetone	MWCNT	Mechanical mixer	Tensile strength 33% Young's modulus 50%	[29]
Acetone	f-DWCNT	Mechanical mixer	Tensile strength 67.77%	[30]
-	MWCNT	Mechanical mixer	Tensile strength 46% Young's modulus 1.18%	[31]
-	f-MWCNT	Mechanical mixer	Tensile strength 55% Young's modulus 1.35%	[32]

6. Influence of graphene on various mechanical and physical properties of epoxy nanocomposites

Graphene exhibits many specific and useful properties, such as a large surface area (2630 $m^2 \cdot g^{-1}$) [33-35], excellent thermal conductivity (5000 $Wm^{-1} \cdot s^{-1}$) [36], a very high young's modulus (1 TPa) [37], a high value of white light transmittance of 97.7% [38], and exceptionally high room-temperature electron mobility of 2.5×10^5 $cm^2 \cdot V^{-1} s^{-1}$ [39]. Recent years have seen a significant increase in research interest regarding these exciting features as a result of scientific and technical advancements. Figure 5 shows the structure of graphene (a single layer of graphite).

The low interaction of graphene sheets with the epoxy matrix, which results in poor mechanical properties as compared to the neat epoxy, is a significant problem for fabricating GNP nanocomposites [40]. The challenge of evenly dispersing the GnP nanoparticles within the epoxy to achieve uniform characteristics is a related problem. Graphite in its layered structure has little surface functionality, quite like carbon fibres after manufacture [41]. Several surface modification methods have been developed for carbon fibres, and the most of these approaches can be used with GnP/epoxy nanocomposites. The surface of GnP has been modified using one of these processes, plasma treatment.

Surface modification of nanoparticles to tune their properties is called functionalization. Functionalization facilitates nanoparticle dispersion in different solvents and optimises the active sites on the nanoparticle surface. Graphite is thoroughly oxidised and exfoliated to produce Graphene oxide (GO), which has a variety of oxygen functional groups with clear chemistry [42]. It is generally achieved by treating graphite with strong oxidising agents and mineral acids, most commonly via treatments with $KMnO_4$ and H_2SO_4 as in the Hummers technique [43] or $KClO_3$ (or $NaClO_3$) and HNO_3 as in the Staudenmaier [44] or Brodie [45] methods, or some combination of these methods. Because of the absence of a single definite analytical approach to characterise this substance, there is no clear model to define the precise structure of GO. The majority of the functional groups, such as hydroxyl and epoxide, are considered to be concentrated most in the particle surface of the graphene layers, but it is generally understood that carboxylic groups are primarily found towards the edge [46]. Table 2 shows the detailed results of various dispersion methods of graphene with epoxy and the properties enhancement.

The polar character of the oxygen functional groups on the GO surface makes it hydrophilic. GO may be distributed in a variety of solvents, but water does so exceptionally well [41]. Furthermore, the most effective process for producing graphene on a large scale at the moment is based on the exfoliation of graphene oxide and reduction of graphene [47]. Chemical functionalization has been used to create solution processable functionalized graphene (SPF-Graphene), and both covalent and non-covalent functionalization's of graphene have been studied [48].

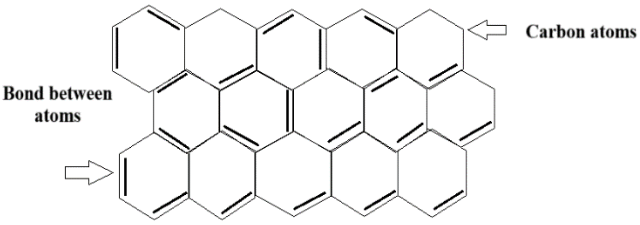

Figure 5. Structure of Graphene (Single layer of Graphite).

Table 2. Different dispersion method of graphene with epoxy and the properties enhancement.

Type of solvent	Type of fillers	Dispersion method	% Enhancement	Ref.
Acetone	GO	Rotary evaporation + water bath	Tensile strength 37%	[53]
Acetone	r-GO	Bath sonic + mechanical	Tensile strength 2.6% Elastic modulus 11%	[54]
Acetone	GO	Bath sonic + mechanical mix	Impact strength 80%	[55]
DER 331	Graphene-nanoplate (GnP)	Bath sonic + mechanical mix	Tensile strength 11%	[56]
-	GO	Bath sonic + mechanical mix	Impact strength 138.12% Glass transition temperature (°C) 33.05	[57]
THF	PVI-g-GO	Bath sonic	Tensile strength 60% Elastic modulus 45.5%	[58]
-	GO	Bath sonic + mechanical mix	Tensile strength 12.6% Glass transition temperature (°C) 5.71	[59]
Acetone	m-GO	Bath sonic + mechanical mix	Tensile strength 18.8% Elastic modulus 42.2%	[60]
Acetone	m-GO	Bath sonic + mechanical mix + ball mill	Tensile strength 63.2% Elastic modulus 12% Glass transition temperature (°C) 1.6	[61]
THF	m-G	Mechanical mix	Tensile strength 28% Elastic modulus 23.6%	[62]
THF	m-G	Bath sonic + mechanical mix	Tensile strength 47.8% Elastic modulus 9.5%	[63]
Acetone	m-GO	Bath sonic + mechanical mix Mix + ball mill	Tensile strength 46% Elastic modulus 10.9%	[64]
Acetone	r-GO	Bath sonic + mechanical mix	Tensile strength 61.4% Elastic modulus 16.5% Glass transition temperature (°C) 3.9	[65]

Table 2. (Continued).

Type of solvent	Type of fillers	Dispersion method	% Enhancement	Ref.
Acetone	m-GO	Bath sonic + mechanical mix Mix + ball mill	Tensile strength 31.8% Glass transition temperature (°C) 18	[66]
DCM	m-GO	Mechanical mix	Tensile strength 46.2% Elastic modulus 31.7% Glass transition temperature (°C) 4.9	[67]
DMF	m-G	Bath sonic	Tensile strength 47.3% Elastic modulus 21.7%	[68]
DCM	m-GO	Bath sonic + mechanical mix	Tensile strength 20.2% Elastic modulus 19.3% Glass transition temperature (°C) 11.4	[69]
Acetone	G	Bath sonic + mechanical mix	Tensile strength 14.1% Elastic modulus 24% Glass transition temperature (°C) 5.1	[70]
Acetone	GO	Bath sonic + mechanical mix	Tensile strength 24.4% Elastic modulus 14.4% Glass transition temperature (°C) 9.3	[71]
DMF	m-G	Bath sonic	Tensile strength 31.8% Elastic modulus 34.1%	[72]
Acetone	G	Bath sonic + mechanical mix	Elastic modulus 11% Glass transition temperature (°C) 11	[73]
Acetone	GO	Bath sonic + mechanical mix	Glass transition temperature (°C) 7.6	[74]
Ethanol	r-GO	Bath sonic + ball milling	Glass transition temperature (°C) 11	[75]

Table 3. Representative examples of properties improvements in Graphene-Epoxy composites.

Epoxy system	Graphene content	Property	% Enachement	Ref.
Epoxy (YD-128 + DDM)	1.0%	Impact strength fracture toughness	80% 98%	[76]
Epoxy (DETDA + DGEB-F)	0.8% 5.0%	Tensile strength Elongation at break Thermal conductivity	37% 63% 2.5 times	[77]
Epoxy (DER 331)	1.0%	Tensile strength Flexural strength Thermal conductivity Dielectric constant	11% 17% 126% 171%	[78]
Epoxy (CYD-128)	1.0%	Impact toughness Glass transition temp (T_g)	138.12% 33.05°C	[79]
Epoxy (DGEBA + TETA)	0.25%	Tensile strength Young modulus	60% 45.5%	[80]
Epoxy	0.3%	Tensile strength Flexural strength Glass transition temp (T_g)	12.6% 10% 5.71°C	[81]
Epoxy (DGEBA)	0.1% 0.2% 0.2%	Fracture toughness Fracture toughness Glass transition temp (T_g)	24% 52% 11°C	[82]

In order to alter the surface characteristics of the material and improve the interaction with epoxy polymers, chemical functionalization of graphene is highly interesting. It can also increase the material's solubility and processability [49-52]. In an epoxy-based nanocomposite containing graphite nanoplatelets, the ultrasonication and UV/ozone treatment of the graphite improved the exfoliation and dispersion of the graphite inside the matrix. Table 3 shows the representative examples of property improvements in graphene-epoxy composites.

7. Influence of NDs on various mechanical properties of epoxy nanocomposites

ND is a member of the large family of amorphous, dense, and porous nanocarbons that also includes fullerenes, CNTs, and graphene. In the last decade, not only the sp^2 carbons like fullerenes and CNTs came into focus but also the nanoscopic version of the sp^3 carbon, namely nanodiamonds. Nanodiamonds were discovered and initially studied in the 1960s in the former USSR. There are several methods available for the synthesis of nanodiamonds, such as the detonation technique, CVD, etc. The main advantages of NDs particles are the ease and diversity, with which they can be functionalized and their unique properties: a diamond structure that provides superior young's modulus, hardness, high thermal conductivity, a low coefficient of friction, and chemical stability.

In comparison to 1-D or 2-D nanofiller, which have at least one substantially bigger dimension, the small size of an NDs particle in all three dimensions (0-D) translates into an orders of magnitude higher number of nanoparticles in the matrix at any given loading [83]. The mechanical characteristics and structural integrity of NDs (small diameters of 5 nm on average; a big and accessible surface area of 300 $m^2 \cdot g^{-1}$ to 500 $m^2 \cdot g^{-1}$; and a rich, tailorable surface chemistry) make them a strong candidate for the best polymer matrix reinforcement. Table 4 shows the comparison of engineering properties between NDs, titanium, and stainless steel. Recently, carbon nanotubes (CNTs) and nanodiamonds (NDs), two allotropic forms of carbon that are nanometre-sized and represent graphite and diamond, respectively, as reinforcing agents in polymeric matrices, have received a lot of interest [84,85]. Detonation nanodiamond (DND) with a sp^3 carbon-carbon bond is one of the most promising candidates for constructing extremely strong nanocomposites among them [86]. Recent investigations have shown that an air oxidation technique significantly improves the purity of NDs powders, allowing control of the NDs' surface chemistry, sp^2 to sp^3 carbon ratio, and crystallite size [87].

Epoxy, a thermosetting polymer, is frequently used in the aerospace, ship building, and sporting goods sectors as a matrix material for carbon-fiber reinforced composites. Numerous kinds of nanofiller have been researched to strengthen the epoxy matrix [88]. The production of NDs-epoxy composites with NDs contents up to 35 vol% improved the mechanical properties of the epoxy. By using nanoindentation to evaluate hardness and Young's modulus, these composites' hardness and scratch resistance were both enhanced by 300% and 700%, achieving modulus values of up to 20 GPa, respectively [89]. Tribological tests revealed that an alumina counter body was harmed by the NDs-epoxy agglomerates present in these composites, exhibiting a very high hardness of the agglomerates that may replace micron-sized diamond particles in drilling and cutting tools. Epoxy composites with 7.5 vol% NDs found their average macroscale friction coefficients reduced by four times, which is close to 0.1 [90].

Lower NDs concentrations can also be used to enhance the mechanical properties while large NDs loadings provide impressively high hardness and Young's modulus in the epoxy-NDs composites. The addition of 0.5% as received NDs enhanced the decomposition temperature while simultaneously increasing the Young's modulus, which was determined in tensile testing. However, due to poor NDs dispersion, the storage modulus of the epoxy composite was extensively reduced, emphasising the importance of a good dispersion to optimise the mechanical properties of NDs-polymer composites [91]. For covalent binding of NDs with the epoxy matrix, it was aimed at forming the strongest NDs polymer interface. This happened as NDs terminated with reactive amino groups was synthesised by linking ethylenediamine to the NDs-COOH surface via an amide bond. Tetrahydrofuran (THF) was chosen for this purpose as it provides a good dispersing medium for NDs-NH_2, dissolves epoxy resin, and according to a previous report, does not react with components of the epoxy system [92].

The first experimental demonstration of epoxy resin curing simply by NDs-NH_2 (with no additional molecular curing agent) is a noteworthy outcome of this work. This is owing to the many reactive amino groups that were added to the NDs surface [93]. These composites that were NDs-NH_2-cured displayed extraordinarily high Young's modulus of up to 20 GPa. These covalently bonded epoxy-NDs-NH_2 composites' tribological characteristics were also investigated. When compared to composites created with up to 50% of NDs as received, a composite with a high content of NDs-NH_2 (33 vol%) has a reduced friction coefficient of up to 54% [94]. This friction coefficient shows the potential of the composite for tribological applications because it is comparable to that of carbon films made from carbides or those resemble diamonds. The various NDs dispersion techniques with epoxy and the resulting characteristics enhancement are shown in Table 5.

Table 4. Comparison of Engineering Properties between Nanodiamond, Titanium and Stainless Steel.

Properties	Nanodiamond	Titanium	Stainless steel
Hardness ($kg \cdot mm^{-2}$)	10,000	230	210
Young's modulus (GPa)	1000	120.2	215.3
Bulk modulus (GPa)	442	108.6	166
Thermal conductivity ($watts \cdot cm^{-1}$)	20	0.21	0.16
Thermal expansion ($°C^{-1}$)	1.1	1.8	17.2

Table 5. Different dispersion method of Nanodiamond with epoxy and the properties enhancement.

Type of solvent	Type of fillers	Dispersion method	% Enhancement	Ref.
Ethanol	m-NDs	Bath sonic + mechanical mix	Tensile strength 81% Elastic modulus 80%	[25]
Ethanol	A-NDs	Bath sonic + mechanical mix	Tensile strength 70%	[95]
-	m-NDs	Bath sonic + mechanical mix	Tensile strength 1.5 times Elastic modulus 2.5 times	[96]
-	NDs	Bath sonic + mechanical mix	Tensile strength 13% Elastic modulus 28% Hardness 11%	[97]
THF	NDs	Bath sonic + mechanical mix	Tensile strength 20% Wear rate 95%	[98]
THF	NDs	Bath sonic + mechanical mix	Elastic modulus 470% Hardness 300%	[99]

8. Conclusion

In this paper, we have reviewed the research carried out on various nanoparticle-reinforced thermoset nanocomposites. From these studies, it was found that the incorporation of nanoparticles such as CNT, GnP, and NDs into the matrix improved the properties of the base polymer material. This review has highlighted the important recent advances in the dispersion method of NDs, MWCNTs, and graphene with epoxy matrix and how dispersion affects the mechanical properties of composites. Homogeneously dispersed nanofiller particles in the epoxy matrix play a key role, mainly for the mechanical properties. The interfacial strength between filler and polymer is a very important factor because a lack of adhesion between the two phases will result in early failure. When the chemically modified NDs, MWCNTs, and graphene were used as filler materials in the polymer matrix, the properties were improved, but they carried some residues and functional groups that were left behind during this process. Thus, further improvement of the composite is a challenging affair. However, for obtaining further improvements in the quality of NDs, MWCNTs, and graphene, we have to adapt another method.

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