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REVIEW

A review on the recent advances on improving the properties of epoxy nanocomposites for thermal, mechanical, and tribological applications: challenges and recommendations

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ABSTRACT

Epoxy nanocomposites are progressively used in the field of mechanical friction because of their unique advantages of lightweight, high strength, wear resistance, and resistance to load. Reports have it that epoxy nanocomposites do face mechanical properties degradation, hence limit their friction and wear performance over a long period of exposure. The review focused on recent advances on the properties improvements of epoxy nanocomposites for mechanical and tribological applications. Thus, the review study summarizes the effects of nano-inorganic and carbon based nanofillers on the thermal, mechanical, and tribological properties of epoxy matrix. It was concluded with advancement, challenges, and recommendations.

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Epoxy; nanocomposites; nanofillers; mechanical properties; thermal stability; tribological properties

1. Introduction

In recent years, researchers and industries have greatly focused their attentions in light weight materials for the design and fabrication of components for use in aerospace, automobile, and marine applications. However, both metal matrix composites and polymer matrix composites materials have been employed in the manufacturing of parts for mechanical and tribological applications. However, polymer composites have proven to be a promising material for mechanical, thermal, and tribological applications over metal based composites. Owing to their outstanding properties, such as mechanical strength to weight ratio, excellent thermal stability, as well as wear resistance and chemical resistance behavior.^[1, 2] Furthermore, the self lubrication and supreme neatness of polymer composites remain its attractive advantage and reported as its beneficial influence when used in tribological applications.^[3,4] For mechanical applications, the adoption of polymer composites as structural material has received considerable attention based on their mechanical load-bearing capacity, strength and stiffness, and cost effectiveness.^[5–7] The futures, which have also contributed to the usage of polymer composites as choice friction material for industrial and technological applications remain the opportunities in easy modification of their properties with unique additives, such as micro/nano ceramic particulates and fibers. Also, recent studies have revealed that the introduction of rigid particles into polymer matrix do result to significant increment in

strength and toughness over pure polymers.^[8] Hence, the reinforcement of polymer matrix composites with additives materials has been described as the major factor on improving their thermal, mechanical, and tribological properties. In present day, different type of nanoparticles have widely been adopted in the preparation of nanocomposites, like epoxy nanocomposites, polyester nanocomposites, polypropylene composites for thermal insulation, mechanical, and tribological applications.^[9–11] Ever since the potential properties of polymer nanocomposites were realized at Total research laboratory, much studies have been carried out on polymer nanocomposites employing nano particles fillers be it ceramics or metallic type and remarkable improvements and benefits in several properties have been presented.^[12] However, epoxy as a thermosetting polymer has widely been the most recent matrix polymer over other thermoset polymer matrices in the development of polymer nanocomposites for many applications^[13] due to its adhesive strength, chemical stability, and electrical insulation.^[14–20] Nowadays, epoxy is greatly used in automobile, aircraft, and railway transportation system for tribological applications. Although, the limitation of epoxy in tribology applications is relatively to its poor wear resistance.^[21] Regards with the extensive use of epoxy for tribological and mechanical purposes, improving its tribology behaviors becomes so paramount to researchers and industries. The incorporation of nanofillers, for example carbon nanotubes, graphene, nano ceramics, and

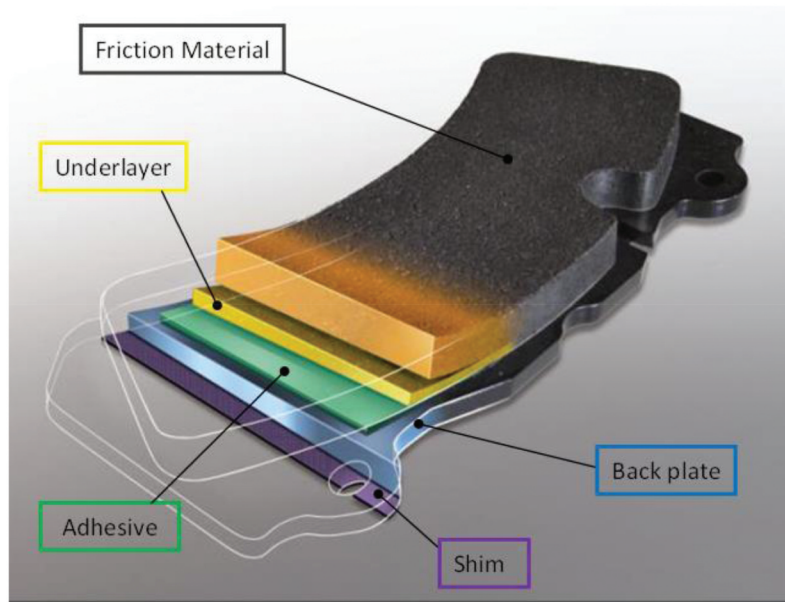


Figure 1. A typical components of a brake pad system^[30,31].

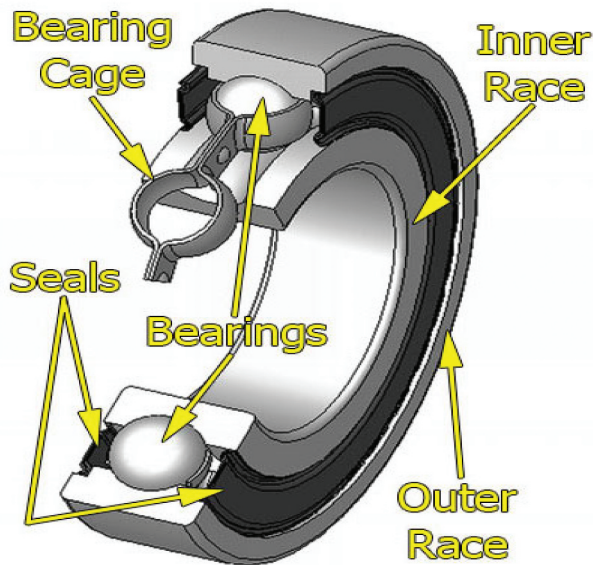


Figure 2. A schematic diagram of ball bearing system.^[32]

nanowires into epoxy resin has reportedly improved its mechanical properties.^[22–27] More so, the enhancement of epoxy composite tribological properties via micro or nanofillers reinforcement has also been reported over the literature.^[28,29] The reported improvements arise on discovering that the stability of transfer film as to possess self lubricating properties directly affects the reliability of epoxy materials when subject to severe wearing conditions. And this is because of the high friction coefficient of epoxy, which has limited its tribological applications. Therefore, the current review study focuses on recent advances on the improvement of epoxy nanocomposites properties as a friction material for thermal, mechanical, and tribological applications (see Figure 1), as well as its challenges and recommendations for future enhancement.

1.1. Overview of epoxy resin matrix material for both thermal, mechanical, and tribological applications

Over the years, polymer composites have drawn the attention of academia and industries as a promising structural material for automobile, aerospace, and chemical industries due to their lower weight over traditional metallic materials. Various numbers of these applications are tribological components and/or parts, such as cams, brake pad, bearing and seals, where the self lubrication of polymers is of special benefit as can be seen in Figure 2. The features, which have made polymer and polymer composites so attracting for industrial applications is the possibility of tailoring their properties,^[28] easy process ability and good development prospect^[33–37] and cost effectiveness.^[38] Among polymer matrices, epoxy matrix has been found so promising in tribological applications, owing to its low density, and anti-corrosion. Further, the low shrinkage, adhesion ability, and high strength of epoxies are added advantages of employing epoxy resin as better matrix material over other polymers.^[38] Due to these characteristics, epoxy resins have been used widely as matrices in several applications.^[39] Epoxy resin as an organic polymer is processed from low molecular weight oligomers, which constitute two or more epoxy groups per molecules. And the most common oligomers (prepolymers) are diglycidyl ethers especially the diglycidyl ether of bisphenol A. As such, the linear epoxy prepolymers are cross linked using curing agents, such as diamines and acid anhydrides that contain active hydrogen, which reacts with the epoxy groups. However, the most essential epoxy resins are determined via the existence of epoxy group of three member ring of two carbons and oxygen atoms.^[40]

The cross linking process in the production of epoxy resins are also achieved through catalyst reaction between epoxy oligomers. Hence, all these process makes epoxy resin in depicting acceptable properties, such as toughness, low shrinkage, solvent and chemical resistance, hardness, and good adhesion to substrate. Although, such notable properties depends on the curing agent used.^[41] The epoxy resin as thermosetting polymer possesses an excellent adhesion due to the presence of epoxy groups in its structure. Due to this, its interaction with the active hydrogen groups when applied on the surface of metallic material basically served as a protective coating. In addition, as a coating material, its application on the surface of metal parts has reportedly improved the wear resistance behavior of such metal.^[42] Thus, epoxy matrix composites are however, in recent time utilized as new composite material for mechanical friction applications as a result of their unique advantages, such as lightweight, high strength, abrasion resistance, and resistance to load. However, epoxy resins as the commonly used polymer matrices in advanced composite materials for engineering and structural applications is limited by the nature of its cross linking structure of 3-dimensional network, followed by their inherent brittleness.^[42] This existence of brittleness in epoxy has usually contributed in the abrasion of the material during performance. For this reason, several studies have focused on the process of compounding epoxy resin with other materials in order to obtain better mechanical friction reduction effect. However, the current review focuses on the recent advances on improving the thermal, mechanical, and tribological properties of epoxy composites via nano-inorganic ceramic and carbon based nanofillers, as well as their processing methods, challenges and recommendations.

1.2. Effects of inorganic nanofillers on the properties of epoxy matrix nanocomposites for thermal, mechanical, and tribological applications

Inorganic nanofillers are refers as particulate materials with a property size, which is in a range of nanometers. The exceedingly large interfacial area of such nanofillers with polymer matrix and size dependent physical properties as a result of their dimensional feature gives numerous outstanding properties over conventional fillers. Reinforcement fillers are forms of material, especially particulates, that is been incorporated into polymer matrix structure to produce polymer composite materials.^[43] And these fillers are usually in the composites so as to improve or incorporate various properties, such as dielectric, mechanical, and thermal.^[43] In addition, chemical structure and concentration of fillers are majorly a factor that determines composites properties. Moreover, one of the most promising means to enhance the behavior and

performance of polymeric materials involves developing polymer nanocomposites.^[44] As such, with the development in the nanotechnology, followed by the easy production of nanomaterials, the introduction of nanofillers to blend polymers has recently increased. Along this line, as hardness of a material is an important parameter influencing the wear behavior of composite,^[45] Verma et al.^[38] studied the effects of inorganic nano-alumina (Al_2O_3) on the hardness, friction and wear properties of epoxy matrix composite. To study the effect of particle morphology on the tribological behaviors, the author adopted two different shapes (nano rod and spherical shape) of Al_2O_3 nano particles. The reinforcement of the epoxy nanocomposites with the nano rod and spherical Al_2O_3 nano particles were prepared by cross linking process at 0.5, 1.0, and 1.5 wt% concentration of Al_2O_3 . The hardness and tribology properties were determined using Vickers micro hardness tester and pin-on-disk tribometer, respectively. In the study, pin of nanocomposites was tested against hard steel counter surface of hardness 60 HRC. The results showed that the nano- Al_2O_3 particles were homogeneously dispersed in the epoxy matrix with random orientation especially in the case of spherical nano- Al_2O_3 . Furthermore, the results demonstrated that the incorporation of the nano Al_2O_3 filler improved the hardness of the epoxy nanocomposites in comparison with the unreinforced epoxy in respective of the reinforcement morphology and weight percent concentration. At 1.5 wt% nano spherical Al_2O_3 loading, 31.4 HV optimum hardness of the epoxy nanocomposites was recorded, which is of 10.82% higher that the untouched epoxy. While in the case of nano rod Al_2O_3 , the optimum micro hardness was 31.2 HV at 1.0 wt% and was observed to be 10.11% greater when compared to that of unreinforced epoxy. In addition, the introduction of the 1.0 wt% spherical Al_2O_3 into the epoxy matrix attributed to the less coefficient of friction and as such leads to the reduced wear rate of the epoxy nanocomposites. It can be deduced that the higher hardness and improved wear resistance of the nanocomposites was as result of the strong interfacial bonding between the epoxy matrix and nano- Al_2O_3 particles. Although, the only challenge is that the strength and modulus of the nanocomposites decreases beyond 1.0 wt% spherical Al_2O_3 loading due to the presence of agglomeration. Alhazmani et al.^[46] investigated the tribological and mechanical properties of reinforced epoxy hybrid nanocomposites. In the study, nano Al_2O_3 and nano silicon carbide (SiC) were employed as the reinforcing phase material. The Al_2O_3 and SiC or hybrid of them was introduced into the epoxy resin at various wt% ratios by ultrasonic system technique. The tensile properties of the epoxy nanocomposites were obtained using small punch testing and indirect tension testing method. Meanwhile pin-on-ring wear testing was carried out to examine the wear

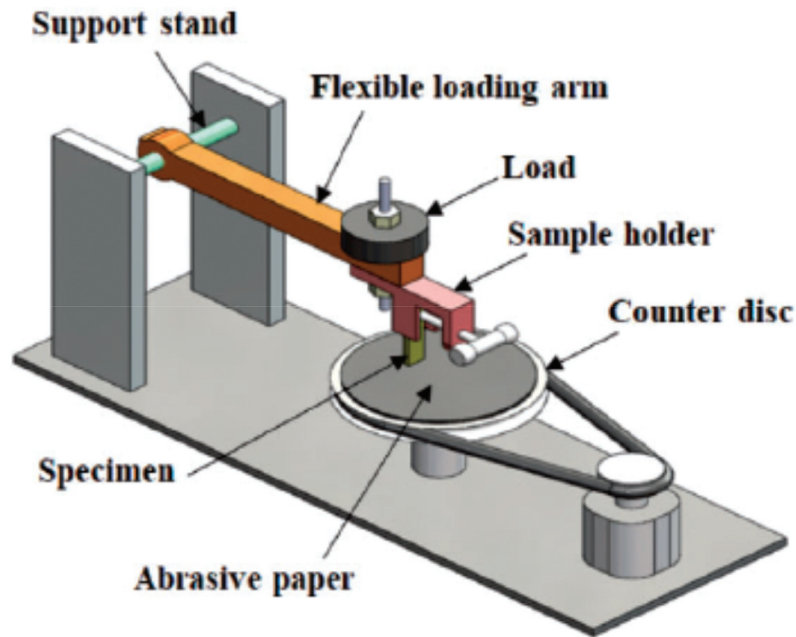


Figure 3. The schematic illustration of pin-on-disc wear test machine^[27].

performance of the Al_2O_3 reinforced SiC/epoxy nanocomposites against bare-wood sandpaper disk with 220 grit size. The results indicated that the incorporation of the nanoparticles be it Al_2O_3 and SiC, improves the wear resistance of the epoxy matrix. In addition, the epoxy composite with nano- Al_2O_3 exhibited better wear resistance than that of SiC/epoxy nanocomposite and the hybrid nanocomposite. From the study, it was reported that the tensile strength and tensile modulus of the epoxy were decreased by incorporation of the Al_2O_3 nanoparticles into its matrix. Meanwhile, it was noted that the Al_2O_3 additive influences the kinetic energy of the epoxy composites. And this in turn result in

reinforcing the epoxy by absorbing kinetic energy, hence, resulted in reducing the composite plastic deformation.^[47] More so, adding nanofillers to epoxy resin could affect the heat generation at the contact surfaces; however, contribute in reducing mass loss of the material during wear performance. This could be the point behind the better tribological properties reported via the incorporation of Al_2O_3 additives in the epoxy matrix. In another study, Youssef et al.^[27] investigated the effects of TiO_2 nanoparticles on the hardness and wear behavior of glass fiber/epoxy composites. This is as a result of TiO_2 being cost effective and as a safe filler material^[48] with enhanced mechanical and

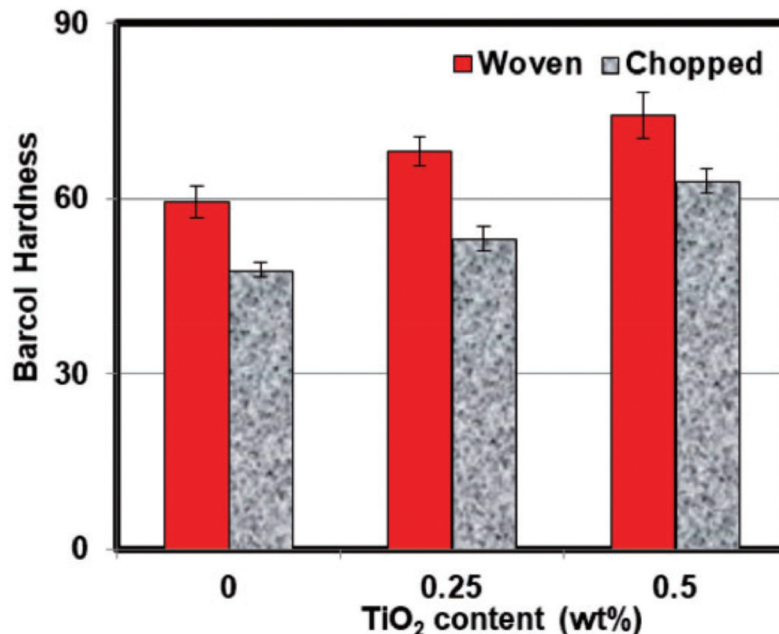


Figure 4. The effects of nano- TiO_2 particles on the hardness of pure woven and chopped glass fibers/epoxy composites^[27].

physical properties on polymers.^[49] In the study, different weight fraction (0.25 wt % and 0.5 wt %) of TiO₂ were added to the pure epoxy and as secondary reinforcement nanofillers. The pure and nano-filler composites were prepared by vacuum resin infusion process. The composite hardness was characterized using PCE-1000 N Hardness Tester Instrument. And the abrasive wear test was performed by pin-on-disk technique as can be seen in Figure 3. The disc was provided with an abrasive alumina paper of 400 grits. From the study, results demonstrated that the incorporation of the TiO₂ nanoparticles into the glass fiber (woven and chopping)/epoxy composites yielded better hardness in comparison with neat glass fibers/epoxy composites as showed in Figure 4. More so, similar result was obtained in a particular research as reported over the literature.^[50,51] However, such improvement in hardness, which resulted from the addition of TiO₂ nanoparticles, could be ascribed to the high intrinsic hardness of the nano-TiO₂ particles. Again, as the load is applied from the hardness indenter, there is an increase in compressive force. Thus, this indenter presses the epoxy matrix and subsequently, the fibers and nanoparticles touch each other and possess resistance. Furthermore, embedding of TiO₂ nanoparticles in the chopped glass fiber/epoxy composites and that of woven glass fiber/epoxy composites leads to the increased wear resistance of the nanocomposites over the neat woven and chopped glass fiber/epoxy composites. As the abrading distance increases, a notable improvement was observed on incorporating 0.5 wt% TiO₂ to both chopped glass fiber/epoxy composites and woven glass fiber/epoxy

composites. Above 0.5 wt% TiO₂ loading, more increase in wear resistance occurred. This indicates that the present of TiO₂ nanoparticles in the epoxy composites enhances the wear resistance due to the rolling action of TiO₂ nanoparticles, which hinders the rise in the friction force. Again, existence of the TiO₂ nanoparticles in the contact area reduces the stress concentration on either woven or chopped glass fibers, hence, prevented the epoxy resin matrix in the interfacial area from being subjected to mechanical and thermal failure.^[52] This increase in wear resistance as the wt% TiO₂ increases evidenced that the TiO₂ nanoparticles played a vital role in reducing the friction coefficient due to the good adhesion between the fibers and the epoxy matrix. And a closer look at Figure 5 clarified this observation particularly on TiO₂/Woven glass fiber/epoxy nanocomposites. In conclusion, the investigators recommend that if the mechanical properties are important parameter for the applications (automobile and aircraft), reinforced woven glass fiber/epoxy composites should be considered. But if time is a critical issue in the industry during fabrication, filled chopped glass fiber reinforced epoxy should be selected.

In another study, to meet up the requirements of high corrosion resistance, wear resistance, and self lubrication of composite coatings basically for marine application, Ying et al.^[53] prepared epoxy matrix composites coatings, which contain PTFE and TiO₂ nanoparticles on steel substrate. The TiO₂ nanoparticles filler was modified with silane coupling agent (KH570). For the section morphology, tribological, and corrosion

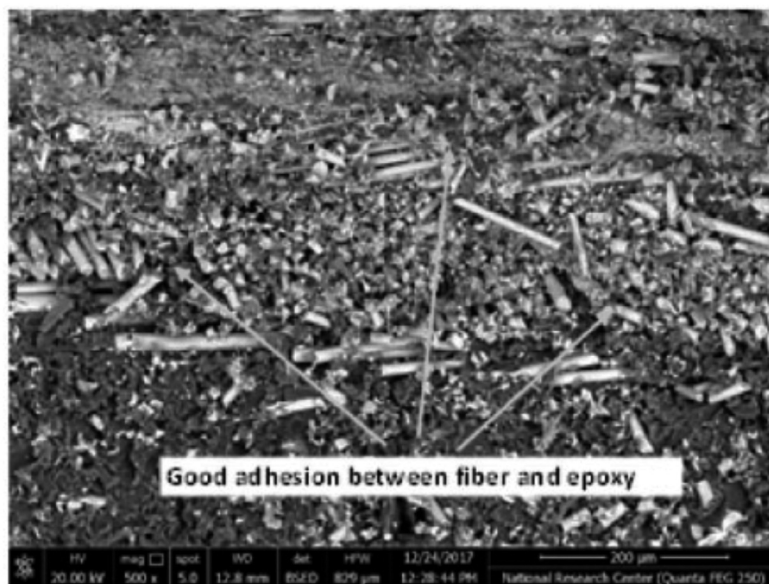


Figure 5. The scanning electron microscope (SEM) image of woven glass fiber/epoxy composite reinforced with 0.25 wt% TiO₂ nanoparticles^[27].

resistance properties of the prepared coating, that is neat epoxy, epoxy-PTFE, and the composite coating with modified and unmodified TiO₂ nanoparticles were examined using SEM, friction-abrasion testing machine, and an electrochemical workstation. The obtained results showed that the introduction of the modified-TiO₂ particles into the epoxy-PTFE composites coatings led to good mechanical properties, such as section toughness, hardness, and binding force when compared to the neat epoxy, epoxy-PTFE, and unmodified TiO₂/epoxy-PTFE composites. Furthermore, with the synergistic action of the friction reduction of the PTFE and dispersion improvement of the TiO₂ nanoparticles, the dry coefficient of friction was noticed to decrease by more than 73%. On the other hands, modified TiO₂ have no much influence on the water contact angles of the coating. However, a larger water contact angle, and uniform and compact microstructure made the composite coating embedded with modified-TiO₂ nanoparticles to possess good anti corrosion ability, with a minimum corrosion current density of 1.688×10^{-7} A/cm². From the SEM analysis, with modified-TiO₂ nanoparticles, the composite coating fracture surfaces are much rougher and as such could be attributed to the reported dispersive distribution of the titanium dioxide, which prevent crack propagation with better interfacial adhesion in reducing the crack source. The improved toughness of the composites coating could be inferred to the grafting of organic functional groups adsorbed on the surface of the modified-TiO₂ nanoparticles over the unmodified nanoparticles.^[54,55] More so, Abass et al.^[56] reported on the improvement of epoxy nanocomposites using TiO₂ nanoparticles. The epoxy composites, which contain glass fiber as primary and TiO₂ nanoparticles as secondary reinforcing phase was prepared by hand lay-up method. The TiO₂ particles were distributed in the epoxy matrix at different weight percents (1, 3, and 5 wt %). The tensile test and hardness of the samples were conducted using tensile test machine at room temperature and Dorumeter hardness tester type (shore D), respectively. From the experimental results, it was revealed that the tensile strength of the fiber-reinforced epoxy composite increased with the fiber and TiO₂ nanoparticles up to utmost value of 3 wt. %, though after which it decreases. Meanwhile, the modulus of elasticity, tension resistance, and hardness value of the fiber reinforced epoxy composites increased with the increasing fiber loading. In conclusion, it was noted that the incorporation of the TiO₂ nanoparticles up to 3 wt% into the fiber-reinforced epoxy eventually contributed to the nanocomposite mechanical strength enhancement over neat epoxy. In a certain study, it was stated that the addition of small

nanoparticles into polymer matrices usually increase their thermal, mechanical, and tribological properties. Noticing this, Zhang et al.^[57] studied the influence of silica (SiO₂) nanoparticles on the tribological behavior of poly (epoxy resin-bismaleimide diaminodiphenylmethane) (EP-BMI-DDM)-based nanocomposites. The EP-BMI-DDM copolymer reinforced with SiO₂ nanoparticles were prepared through in situ suspension polymerization. And to improve the interfacial adhesion of the SiO₂ particles into the polymer matrix, the nano-SiO₂ particles were organo-modified employing silane coupling agent. As chemical modification of nanoparticles surface could enhance the coupling property between polymer matrix and the fillers.^[58-60] In characterizing the nanocomposites, results of the tensile strength test performed revealed that the composite toughness was improved and such improvement were ascribed to the microcavitations, which were induced by the modified-SiO₂ nanoparticles. The SEM result indicated stress zones in the composites formed by the organo-modified SiO₂ due to high hydrostatic stress below crack tip.^[61] Basically, from the study, localized cavitations at the modified SiO₂/ matrix interface actually induced energy dispersion being found close to the crack tip, hence enhance crack growth resistance of the polymer matrix, however, and improved the fracture toughness. The present of the organo-modified SiO₂ in the polymer matrix also improved the nanocomposites hardness and tensile strength at 2 wt% incorporation as it hinders crack propagation and fracture in comparison with the virgin copolymer. In addition, loading of the organo-modified SiO₂ at 2 wt% played a critical role in anti-friction behavior with optimum friction coefficient of 0.17. In the study, thermal stability of the nanocomposites was determined via differential thermal gravimetric evaluation. It was reported that at the maximal rate of weight loss of the 3 wt% organo-modified SiO₂/EP-BMI-DDM nanocomposite, the temperature reads 452 °C, which is 52 °C greater than the virgin EP-BMI-DDM copolymers of 400 °C value. The outcome of the study shows that the developed nanocomposites with good thermal stability and self lubrication can widely be employed as wearable material under harsh working conditions with high temperature. Also, in a study conducted by Yadav et al.,^[62] it was also reported that the reinforcement of epoxy matrix composites with nano-SiO₂ greatly improved their mechanical properties, such as toughness, stiffness and strength, and similar finding was reported in Zhang et al work. In developing polymer composite material, epoxy is found the most favorable matrix material based on its highly cross linked structure during curing. And as such offers a remarkable improvement in certain properties, for example shear strength,

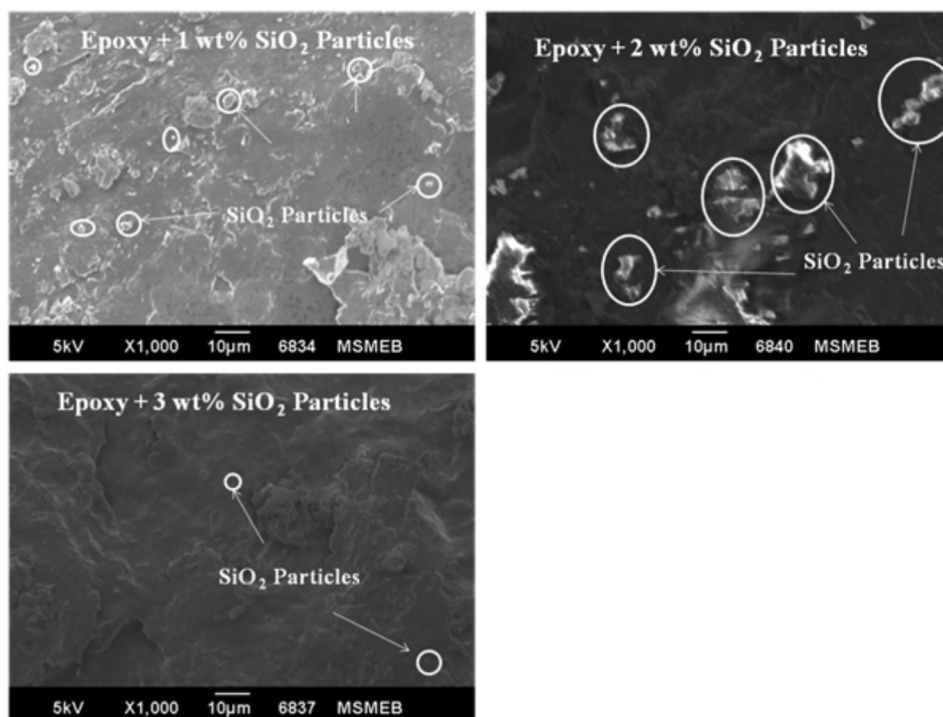


Figure 6. The SEM image of varying nano-SiO₂ particle reinforced epoxy composites^[67].

reduction of friction coefficient, high modulus, and low creep, hence extends the service period of composite component.^[63–66] However, due to the highly cross linked structure of the thermosetting polymer, epoxy material do exhibits brittleness and poor resistance to crack propagation. To address this limitation of epoxy, Christy et al.^[67] concentrate on the development and characterization of epoxy matrix nanocomposites reinforced with nano-SiO₂ fillers. The nanocomposites were prepared at varying concentration (0 to 3 wt %) of nano-SiO₂ particles by ultrasonic vibration assisted processing. The evaluation was on microstructure and mechanical properties. Studying the sample microstructure using SEM, it was observed that at lower wt% of SiO₂ nanoparticles in the epoxy matrix, the SiO₂ are distinctly visible in the matrix. Meanwhile at 2 wt% there is clustering of the SiO₂ particles, but proper dispersion was noticed at 3 wt% SiO₂, although, agglomerations were formed but it was homogeneously distributed as can be seen in Figure 6. Also, the results showed increased tensile strength as wt% of nano-SiO₂ increases up to 3 wt%. Such increment of the mechanical strength could be attributed to the improved interfacial bonding between the epoxy matrix and nano-SiO₂ particle induced by the ultrasonic dispersion process. The bearing capacity of the nanocomposites evidenced its hardness and impact strength enhancement till 3 wt% addition of nano-SiO₂. Incorporating SiO₂ into epoxy matrix network inculcates lower shrinkage on curing, reduces coefficient of thermal expansion, enhancement

in mechanical properties and thermal conductivity.^[68,69] However, to consider epoxy composites as friction material, Dmitriev et al.^[70] investigated the influence of nano-SiO₂ particles on the tribological properties of epoxy nanocomposite. From the study, results indicated that the addition of 5 wt% SiO₂ nanoparticles in the epoxy reinforced composite reduces its friction coefficient. As such position the nanocomposites a choice material for wear applications over pure epoxy material. Furthermore, subjecting epoxy materials to wear by metal surfaces, it normally depicts rather high coefficient of friction, for this causing high wear rate, exacerbate noise, and friction, hence limiting their performance during service. Observing this drawback in epoxy resin, Imani et al.^[71] incorporated nano-SiO₂ particles into epoxy matrix to investigate its effects on the epoxy matrix composite. The friction and wear behavior of the samples were determined by universal tribometer under dry sliding condition on a ball-on-disc configuration. The ball was made of stainless steel with hardness HRC 39. From the results, there is a steady improvement in the composites Vickers hardness, flexural strength and modulus. This was observed with increasing filler fraction of nano-SiO₂ into the epoxy composite and similar trend of properties has been reported in a particular study conducted by.^[72–74] Further, examining the wear behavior of the pure epoxy, a dramatic increase in friction coefficient was recorded at the beginning of sliding wear, which likely ascribe to the gradually increased contact area between

friction pairs. And for the nano-SiO₂ reinforced epoxy composite, similar friction coefficient curve and value were developed in comparison with the pure epoxy, although the friction value was more stable for most of the sliding time as reported by the authors. However, reductions in friction coefficient and wear rate were reported on modification of the nano-SiO₂ reinforced epoxy composites with wax containing microcapsules. Here, the wax aid in forming the thin and continuous transfer film on the steel counter face, thereby resulting in polymer to polymer contact instead of the original steel-polymer counter system. In another study, Zhang et al.^[75] investigated the effects of the dispersion state of SiO₂ nanocomposites on the tribological behavior of short glass fiber reinforced epoxy composites. In order to eliminate abrasion that could be caused by the nanoparticles agglomeration, the SiO₂ nanoparticles were introduced into the short glass fiber (SGF) via in situ synthesized process. The tribology tests were conducted employing pin-on-disc tribometer and 100Cr6 steel disc was employed as counterparts. The results showed that introducing SiO₂ nanoparticles into the SGF reinforced epoxy composites aggravate the abrasion effects, hence lowered the composites tribological performance. The major reason, which could results to this observation, remain the high abrasiveness of SGF, thus the steel counterpart severely scratched by the sliding polymer composites and as such results in severe abrasion of the nanocomposite. In this case, it can be deduced that the expected SiO₂ transfer film, which could have depicts excellent lubrication performance never form. Although, incorporation of the nano-SiO₂ particles into the SGF reinforced epoxy significantly improves the mechanical properties (tensile strength and modulus) of the composites. However, introducing SiO₂

nanoparticles into SGF/epoxy composites as a friction material under severe sliding motion should not be recommended unless there is further addition of self-lubricating material like PTFE, graphite, and/or MoS₂^[76–78] into such compounding epoxy composites. Along this line, Chen et al.^[79] carried out a study on the effect of nanosheets molybdenum disulfide (MoS₂) on the tribological properties of epoxy hybrid composite. The epoxy nanocomposites were fabricated by facile in situ hydrothermal method. The results indicated that embedding MoS₂ into the epoxy hybrid nanocomposite, the nanocomposites exhibited the optimal anti friction and wear resistance. It was reported that the reinforced epoxy composite friction coefficient and wear rate under harsh sliding conditions (against steel ball) decreased by about 80% and 88%, respectively. According to the SEM results, the improved tribological properties of the composite over pure epoxy were attributed to the uniformly dispersion and solid lubrication properties of the MoS₂ on the reinforced epoxy composites. Also, Chen et al.^[80] reported on the influence of MoS₂ exfoliation conditions on the mechanical properties of epoxy nanocomposites. In the study, MoS₂ fillers were produced via chemical exfoliation method and employed as reinforcement phase to prepare the epoxy nanocomposites through casting process. From the experimental results, preparing the MoS₂ fillers through chemical exfoliation, interfacial adhesion strength between MoS₂ and epoxy matrix was enhanced. Hence, the tensile strength and tensile modulus of the epoxy matrix were improved by about 500% and 6800%, respectively, with the incorporation of 1.0 wt% exfoliated MoS₂ nanofillers. However, the study contributes a facial way to produce high performance epoxy nanocomposites. On the other hand, Liu et al.^[81] prepared

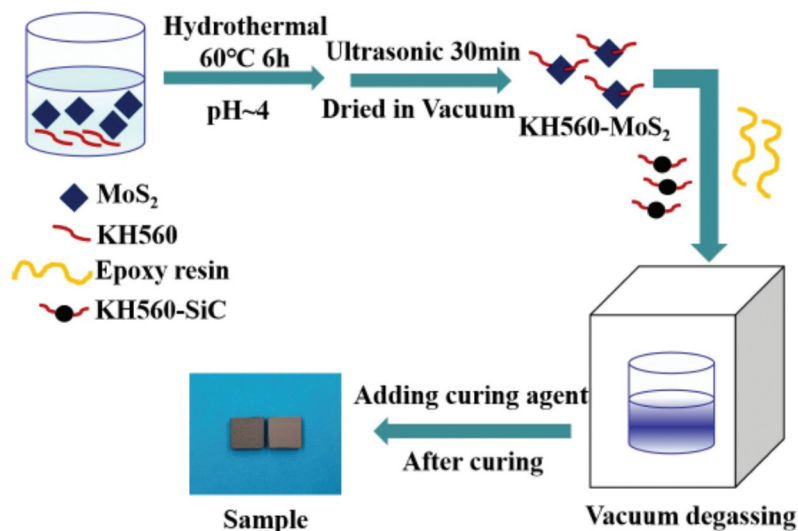


Figure 7. The schematic illustration on the preparation of modified MoS₂ reinforced SiC/epoxy composites^[81].

epoxy composites with different proportions of silicon carbide and MoS₂ powders using hydrothermal and vacuum degassing process as can be seen in Figure 7. Here polyethylene polyamine was the curing agent for the composites mixture. In the study, silicon carbide (SiC) and MoS₂ powders particles were modified by silane coupling agent KH560 as to improve the distribution and avoid agglomeration of the particles into the epoxy matrix. The evaluation was on the concentration effect of modified MoS₂ on the tribological behavior of SiC/Epoxy composites and the wear mechanism of the composite worn surface. The SEM results on examining the microstructure of the fractured sample showed that the modified-MoS₂ particles were uniformly distributed and well dispersed into the SiC/epoxy composites. Hence incorporation of 4 wt% modified-MoS₂ in the epoxy composite, notably affects the behavior of the composites. It was reported that the sample hardness, reduction in coefficient of friction and wear rate were improved in comparison with the pure epoxy, SiC/epoxy, and other concentration of MoS₂/SiC/epoxy composites. Reason was that the present of such weight percent modified-MoS₂ played a role by hindering surface worn out of the composites as a result of the reportedly good interfacial adhesion and transfer film, which must have occurred. In another study, it was found that addition of modified SiC into epoxy matrix reduces its friction coefficient by impeding the tearing of the epoxy composite surface.^[82-84] However, Kadhim^[85] reported on the tribological properties enhancement of epoxy matrix reinforced nano-SiC particle composites. For preparing the epoxy nanocomposites with varying concentration of SiC nanoparticles, mechanical layup technique with ultrasonic method for the dispersion of the SiC particles in the epoxy matrix are used. The friction and wear tests were performed on the pin-on-disc machine against hardened ground stainless steel disc of hardness 55 HRC. On different loading conditions (5, 10, and 15), with sliding speed (1.5 m/s) and sliding time (5secs), results demonstrated significant improvement in hardness, wear resistance and low friction coefficient for 10 wt% SiC incorporation into the epoxy matrix over the neat epoxy and other wt % concentrations. In addition, Naeimirad et al.^[86] studied the influence of shape and filler concentration on the mechanical and physical properties of SiC (nanoparticles and nanowhiskers) reinforced epoxy nanocomposites. The epoxy nanocomposites were prepared at 0.5, 1.0, 2, and 4 wt% of β -SiC nanoparticles and nanowhiskers using a high-intensity ultrasonic liquid processor and casting method. The mechanical, physical, and tribological test of the specimen along with the morphological examination by FT-IR, SEM, and TEM were

conducted. From the mechanical test experimental results, which was also evaluated with theoretical model, results indicated about 20% and 40% improvement in 1.0 wt% nanoparticles and 2 wt% nanowhisker reinforced composites specimen, respectively. Furthermore, tribology results showed that the wear and friction properties were enhanced to about 50% and 30%, respectively, on adding 4 wt% SiC (nanoparticles and nanowhisker) into the epoxy resin. And this is because the nano-fillers are well distributed and dispersed in the epoxy matrix at low weight ratio, however agglomerated above a critical content. It can be deduced that nanoparticles and nanowhiskers form of SiC remain a promising reinforcement phase material on improving the epoxy matrix nanocomposites for mechanical and tribological applications. Although, the SiC nanoparticles reinforced epoxy matrix composites exhibited better mechanical properties. More so, authors like Bazrgari et al.,^[87] Gu et al.,^[88] Mostovoy et al.,^[89] Mohan and Renjanadevi,^[90] Dass et al.,^[91] and Che et al.^[92] reported widely on the improvement of the thermal, mechanical and tribological properties of epoxy and epoxy hybrid composites using inorganic based nanofillers. And their obtain results are summarized in Table 1.

1.3. Effects of carbon based nanofillers on the properties of epoxy matrix nanocomposites for thermal, mechanical, and tribological applications

Over the years, different kinds of nanofillers have been employed to improve the properties of polymer composites. Regards to the topology, these nanofillers can be classified into three categories, such as spherical, rods, fibrous, layered, and flakes nanofillers.^[109,110] Among these nanofillers, for example spherical carbon black (CB), fibrous carbon nanotubes (CNTs), layered graphene (GN), and nanoflakes graphene oxides (GO); all belong to carbon based nanofillers and they are of the same chemical compositions. The used of these nanofillers in several applications is their ability in tailoring the properties of matrix materials indirectly via structural interventions. Thus, researchers and industries recently found the carbon based nanofillers (CNTs, GNPs, and GO) as a promising reinforcement phase material for developing polymer nanocomposites, owing to their excellent properties, such as unique surface area and high aspect ratio, stiffness, and wear resistance.^[111-114] Polymers exhibits desirable properties, such as low cost, corrosion resistance, good friction coefficient, and environmental friendly, but have limitation for thermal, mechanical, and tribological applications over long period of time. However, by incorporating carbon based nanofillers into polymer matrices, the polymers retain their original properties but benefit from enhanced rigidity and stiffness, while still being a lightweight material.

Table 1. Summarization of the processing methods and recent advances on improving the properties of epoxy reinforced nanocomposites for thermal, mechanical, and tribological applications.

Polymer matrix	Nanofillers	Process Method	Mechanical properties			Tribological Properties		Thermal Stability	Ref.
			Hardness	Tensile (MPa)	Elastic Modulus (GPa)	Coeff. of Friction	Wear rate (mm ³ /Nm)		
Epoxy	1.0 wt% Al ₂ O ₃	Cross-linking	31.4	≈74.4	≈3.38	0.51	Improved wear resistance	-	[38]
	3 wt% Al ₂ O ₃	Ultrasonic	-	40.79	≥2.4	-	Improved wear resistance	-	[46]
	0.5 wt.%TiO ₂ /Woven glass fiber	Vacuum infusion	Improved	-	-	Reduced	Improved wear resistance	-	[27]
	Modified-TiO ₂ /PTFE	Solution methods	60	-	-	≤0.10	Improved wear resistance	-	[53]
Epoxy	2 wt % SiO ₂	In situ polymerization	84.3	57.5	-	0.21	Decreased	Improved	[57]
	3 wt.% SiO ₂	Ultrasonic vibration	-	Improved	-	-	-	Improved	[67]
	5 wt.% SiO ₂	Solution Mixing	250	-	3.5	≤0.7	Increased	-	[71]
	3 wt% SiO ₂ /10 wt% SGF	In situ synthesis	-	Improved	Improved	≥0.5	4.0 x 10 ⁻⁶	-	[75]
	MoS ₂	Hydrothermal method	-	-	-	0.1	Improved wear resistance	-	[79]
	1.0 wt%MoS ₂	Casting	-	Improved	174.8	-	-	-	[80]
	10 vol. % SiC	Mechanical layup	58.0	-	-	0.03	2.24 x 10 ⁻⁷	-	[85]
Epoxy	2 SiC wt% nanoparticles	Casting method	84.1	105.4	2.67	0.04	1.2 x 10 ⁻³	-	[86]
	2 SiC wt% nanowhiskers		86.0	115.1	3.23	0.06	4.0 x 10 ⁻³	-	
	1.0 wt% Al ₂ O ₃	Ultrasonication	80	-	-	≥0.5	≤2.5 x 10 ⁻⁶	-	[87]
	Si ₃ N ₄ -PTFE	High pressure compression molding	-	-	-	Improved	Improved	-	[88]
	0.1 wt% BN	Ultrasonication	-	≈45	2.35	-	-	-	[89]
	2 wt% ZnO	Ultrasonication	35	78.07	-	0.34	3.4 x 10 ⁻⁸	-	[91]
	0.1 wt% ZrO ₂ /rGO	Michael addition reaction	-	82.33	1.30	0.8	5.5 x 10 ⁻⁵	Improved	[92]
	0.5 wt% MWCNTs	Calendering	20	-	-	0.1	1.0 x 10 ⁻³	-	[93]
	0.5 wt% MWCNTs	Mechanical mixing	70.5	45	1.73	-	Improved wear resistance	-	[94]
	1.5 wt% CNT	Casting	-	-	3.8	0.1	3.37 x 10 ⁻⁵	-	[95]
	0.4 wt%/3 wt SiO ₂	In situ synthesis	-	-	-	≤0.9	≤5.0 x 10 ⁻⁶	-	[75]
	0.1 wt% MWCNTs	Ultrasonication Treatment	-	75	2.46	-	-	Improved	[96]
	0.1 wt% fluorinated-CNTs	Casting	-	Improved	1.48	-	Decreased in weight loss	Improved	[97]
	0.3 wt% modified-GNP	Mixing/ultrasonication	-	≤65	≈3.75	0.43	3.63 x 10 ⁻⁴	-	[98]
	0.5 wt GNP	Mechanical mixing and sonication	≤80	65	5.35	0.14	5.0 x 10 ⁻⁷	Improved	[99]
4.5 wt GNPs	Solution mixing	85	≈47.5	≤1.35	Improved	Reduced	-	[100]	
1.0 wt functionalized GO	Wet mixing and solvent evaporative	-	62.3	3.02	-	-	Improved	[101]	
0.2 wt% functionalized-GO	Ultrasonication	175	73.0	3.15	0.35	0.55 x 10 ⁻⁶	Improved	[102]	
0.5 wt% modify GO		-	≥35	-	0.41	3.0 x 10 ⁻⁵	Improved	[103]	
Epoxy	2 wt% Al ₂ O ₃ -0.5 wt% GNP	Sonication and ball milling	-	-	Improved	-	-	Improved	[104]
	10 wt% TiO ₂	Ultrasonic dual mixing process	-	82	Improved	-	-	Improved	[105]
	3 wt% SiO ₂	Extrusion	61	43	0.77	Reduced	Improved wear resistance	Reduced	[106]
	1.0 wt% Reduced-GO	Ultrasonication and shear mixing	-	49.8	3.56	-	-	Improved	[107]
	5 wt% Si ₃ N ₄	Hand lay-up	-	473	15.0	-	-	Improved	[108]

As such Campon et al.^[93] studied the dispersion effect of CNTs on the tribological properties of epoxy composites. The epoxy nanocomposites were prepared at 0.1, 0.2, 0.3, and 0.5 wt% multi-wall carbon nanotubes (MWCNTs) by calendaring process. The tribological behavior of the epoxy reinforced MWCNTs nanocomposites were examined using pin-on-disc wear testing machine under different conditions. SEM machine and 3D profilometer were employed to study the samples worn surfaces as can be

seen in Figure 8. From the study, the epoxy nanocomposites with MWCNTs demonstrated a lower weight loss, reduced coefficient of friction and wear rate in comparison with the pure epoxy. The properties response decreases as the MWCNTs wt% increases. Also, the results showed that the 0.5 wt% MWCNTs/epoxy nanocomposites depicted the best tribological behavior. In addition, to design a laminating resin that will meet the standard for motor planes, Mucha et al.^[115] reinforced epoxy matrix with

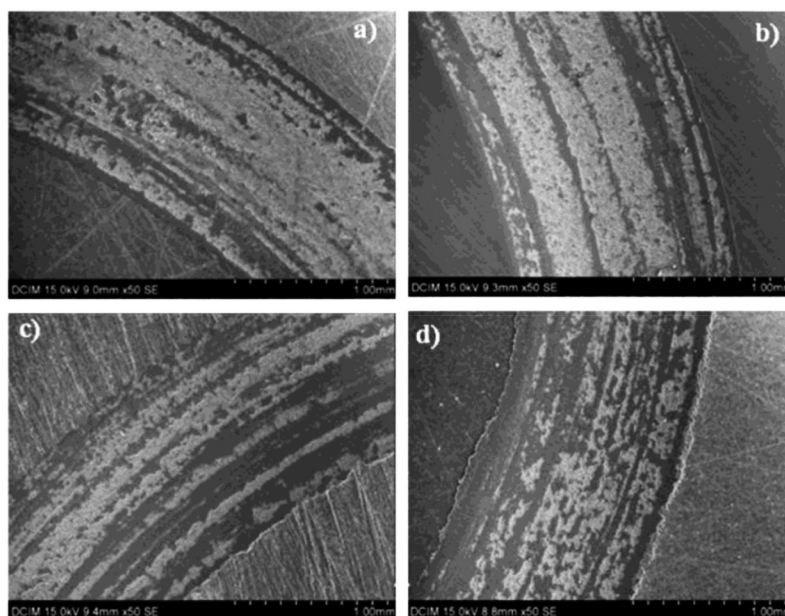


Figure 8. The SEM image of the samples worn surfaces; (a) pure epoxy, (b) 0.2 wt%, (c) 0.3 wt% and (d) 0.5 wt% epoxy nanocomposites^[93].

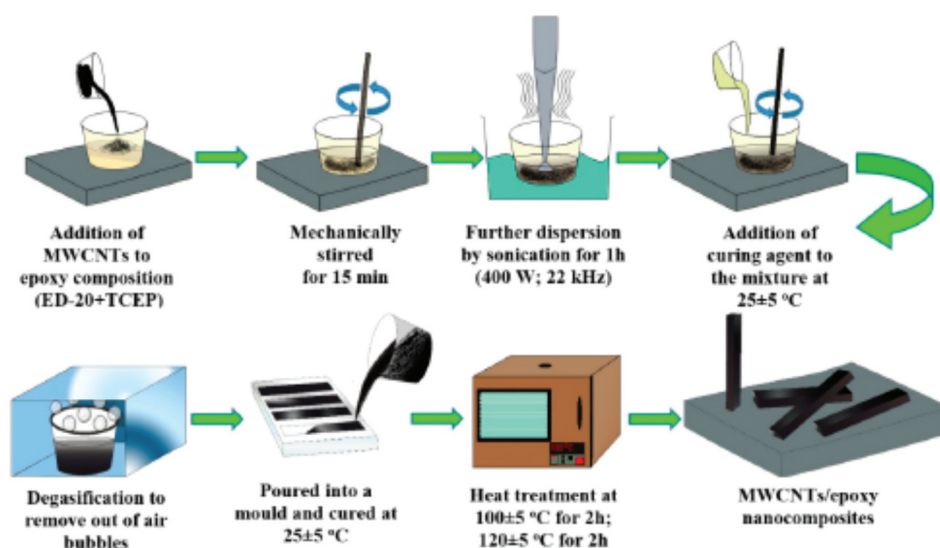


Figure 9. The schematic illustration for the fabrication process of the MWCNTs reinforced epoxy nanocomposites^[96].

MWCNTs at different weight percent concentrations (0 to 2 wt%). Here, the nanocomposites were prepared by mechanical mixing and ultrasound exposure process. The evaluation was on mechanical and tribological properties. The results showed that the best wear resistance was obtained at 0.25 and 0.5 wt% MWCNTs reinforced epoxy nanocomposites. Also, at the same range of concentration, the tensile strength properties result to the highest values with lowest hardness value. This indicates that the lower the hardness of the material, the more it tends to form a carbon film, which could cover the contact surfaces, hence act as a solid lubricant.^[94] Together with the topography and surface imaging analysis, it was concluded that the developed epoxy nanocomposites stand to be a considerable

material for friction system. On the other hand, Sakka et al.^[95] reported on the tribological response of an epoxy matrix reinforced with graphite and carbon nanotubes. The influence of different fillers on the tribological properties of an epoxy matrix structure network were studied by the treated and untreated carbon nanotubes, graphite, and a mixture of graphite and carbon nanotubes. On investigating the friction and wear behavior of the bulk epoxy and the carbon based fillers reinforced epoxy composites adopting a pin-on-disk under dry sliding conditions against 100Cr6 steel ball. Results indicated that the incorporation of fillers into the epoxy greatly improves its mechanical and tribological performance by reducing its friction coefficient and wear rate. Furthermore, the highest coefficient of friction

value of 0.65 and lowest value of 0.1 were recorded with the virgin epoxy and treated CNTs reinforced epoxy composites, respectively. However, of all the samples, the best result was noticed at the treated CNTs reinforced epoxy nanocomposites. It was inferred that the CNTs were well distributed and dispersed into the epoxy matrix owing to the presence of the NH_2 groups. In conclusion, it was deduced that there is no synergetic influence between CNTs and graphite. Zhang et al.^[75] reinforced CNT/epoxy nanocomposites with silica in order to develop epoxy hybrid nanocomposites, followed by the characterization of their tribological behavior. From the experimental analysis, it was observed that the wear resistance of nanocomposites was enhanced. The incorporation of the silica actually attributed to enhanced wear resistance of the composite as the presence of silica nanoparticles on the interface generated transfer films with different structures and functions. The challenge remains that the CNT/silica hybrid could not show any synergic effect on the tribological behavior of nanocomposites. However, there is need for future study in order to understand the mechanism behind such limitation as it was not detailed in the study. Although, it was reported that 0.4 wt% CNTs addition into the epoxy matrix improves its mechanical properties. In addition, Mostovoy et al.^[96] carried out a study on epoxy composites filled with functionalized carbon nanotubes. In the study, amino functionalized MWCNTs were fabricated via chemical modification of the MWCNTs surface employing γ -aminopropyltriethoxysilane (APTES) and dispersed in the epoxy matrix composition. Figure 9 shows the process route in preparing the functionalized MWCNTs reinforced epoxy nanocomposites. On analyzing the samples, the obtained results indicated that the functionalized and chemical compatibility of the modified-MWCNTs reinforced epoxy nanocomposites yielded an increased physico-mechanical properties (bending stress, impart strength, tensile strength and modulus) of the nanocomposites. Here, it was reported that the tensile strength and tensile elastic modulus of the epoxy matrix reinforced at 0.1 wt% $\text{MWCNTs}_{(\text{APTES})}$ increases by 108% and 52%, respectively, when compared with the plasticized epoxy without $\text{MWCNTs}_{(\text{APTES})}$. Meanwhile the tensile strength and tensile elastic modulus of 0.1 wt% $\text{MWCNTs}_{(\text{APTES})}/\text{epoxy}$ nanocomposites increases by 10.3% and 6.65%, respectively, in comparison with that of unmodified 0.1 wt% $\text{MWCNTs}/\text{epoxy}$ nanocomposite. The improved properties of the modified-MWCNTs/epoxy nanocomposites over the neat epoxy and unmodified-MWCNTs/epoxy nanocomposites was attributed to the effective surface modification of the MWCNTs with APTES and the formation of strong interfacial bonding between the epoxy matrix and the fillers. However, the conducted study has proven that it is quite possible to regulate directly operational

properties of epoxy composites by small MWCNTs fillers, which allow in developing epoxy nanocomposites with high performance properties.

Recently, nanocomposites are often utilized in various industrial applications, owing to their specific physico-mechanical properties as nano dispersed particles are reportedly not stress raisers or concentrators in polymer matrix composites.^[97, 116–119] However, to improve the characteristics of epoxy matrix, Amirbeygi et al.^[98] investigated the reinforcing effects of functionalized graphene on the mechanical and tribological behavior of epoxy nanocomposites. The graphene at different content (0, 0.05, 0.1, 0.3, and 0.5 wt %) nanoplatelets were functionalized with aminopropyl trimethoxysilane, which stand as an interfacial modifier. The results indicated that the highest value of interlaminar shear stress and compressive strength were related to the 0.3 wt% modified graphene nanoplatelets (GNP) reinforced epoxy nanocomposites. More so, the addition of the modified GNP into the epoxy matrix, improved the tensile strength and strain to failure only at low concentrations (in particular 0.05 wt %). Furthermore, approximately 40 and 68% decrease of friction coefficient and wear rate, respectively of the nanocomposites were noticed at 0.3 wt % modified-GNP loading. Hence, improved compressive, interlaminar shear stress, tensile, and wear properties in the modified-GNP/epoxy samples were observed on the modified-GNP/epoxy when compared to the unmodified-GNP/epoxy samples. The authors findings revealed that graphene agglomeration occurred on the fracture surface of the 0.5 wt% modified-GNP reinforced epoxy nanocomposites and as such attributed to the main factors responsible for the reduction in the mechanical properties (compressive and tensile strength) of the samples at higher GNP addition.^[120] As reported that graphene nanoplatelet is one of the most used nanofillers to improve the entire mechanical characteristics and tribological behavior of polymer composites owing to their solid lubricant properties and thermal stability, Sukur et al.^[99] carried out a study on the mechanical, tribological, and thermal stability properties of epoxy Phenolic nanocomposites filled with graphene nanoplatelet. The nanocomposites were prepared at different concentrations of GNP. The sliding wear test of the reinforced epoxy nanocomposites were conducted by ball-on-disc tester at room temperature under a constant load and sliding speed in ambient air. From the experimental results, at 1.0 wt% GNP loading, the tensile strength and elastic modulus was recorded to be 74 MPa and 6.2 GPa, respectively. Meanwhile, the friction coefficient and wear rate value were 0.14 and $5 \times 10^{-7} \text{ mm}^3/\text{Nm}$, respectively, which indicates 30% and 74% increment, respectively. In addition, examining the thermal behavior of the samples using thermogravimetric analyzer (TGA), there is a notable increase in thermal stability of the

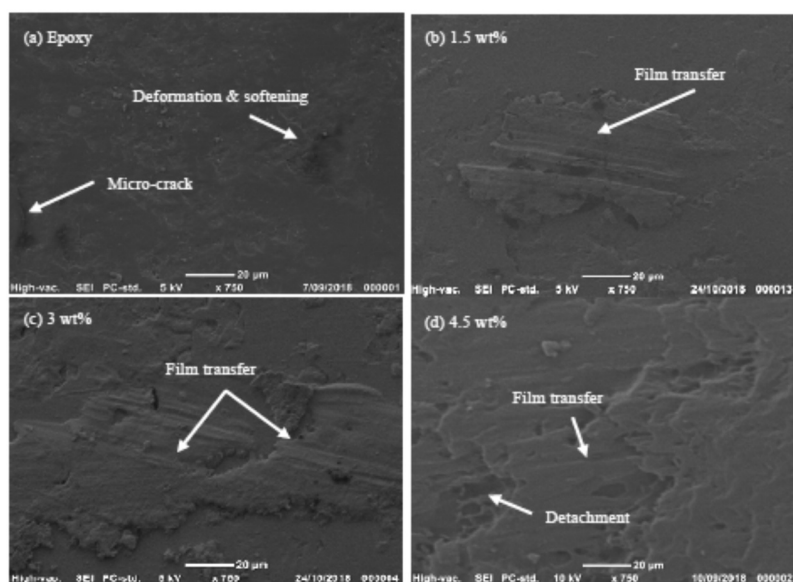


Figure 10. SEM micrograph of neat epoxy and its nanocomposites after adhesive wear performance at 30 N of the applied load^[100].

nanocomposites over the pure epoxy Phenolic resin. Also, with increase of the GNP concentration into the epoxy matrix, the hardness value increases, and such is not the same with the tensile strength which decreases above 1.0 wt % GNP addition into the epoxy phenolic based matrix. This can be described by the fact that the hardness of the nanocomposites is not sensitive to the nanoplatelet agglomeration as much as the basic mechanical properties.^[121] Again such trend in the mechanical properties could be the heterogeneity of the nanoparticles above 1.0 wt% loading, which was revealed in the SEM image presented by the authors. Further, it can be deduced that the 0.5 wt% GNPs incorporation is more effective at stabilizing the friction coefficient and hence reduces its values when compared to other additive ratios. This evidenced that the GNPs greatly act as a solid lubricant between the friction surfaces. The reported increase in hardness and elastic modulus of the epoxy phenolic composites with GNP additive could also attributed to the decreased in friction by reducing contact between the steel ball and developed composites.^[122] It can be concluded that GNP additive and dispersion in epoxy resin have a substantial influence on thermal, mechanical, and tribological behavior of the composites. On the hands, Eayalawwad et al.^[100] investigated the effects of GNPs on the mechanical properties and adhesive wear performance of epoxy-based composites as it is stated that epoxy has a high coefficient of friction,^[123] thus have limits its tribological applications. The influence of the solid lubricant GNPs were evaluated at different weight fractions (0 to 4.5 wt %). The nanocomposites were prepared via mixing process. The effect of the GNPs on the adhesive wear behavior of epoxy was performed by using the block-on-ring against the stainless steel counterpart under dry

condition. The sliding speed was stabled at 2 m/s with applied loads (15, 30, 45, and 60 N). The failure mechanism for both the mechanical and tribological specimens were observed using SEM. The results demonstrated that the incorporation of the GNPs into the epoxy matrix, improved its stiffness and hardness, meanwhile reduces its fracture strength and toughness. Also, from the adhesive wear results, the epoxy matrix depicted high efficiency with the GNP incorporations with good reduction in the specific wear rate and friction coefficient by 76% and 37%, respectively. This improvement is ascribed to the ability of GNPs to produce a stable transfer film. As such, the created transfer film stand as a thin coating layer during the wearing process between the steel counterpart and the worn surface, and hence protect the worn surface (composites) from further material tearing (see Figure 10). Still on improving the properties of polymer matrices, graphene derivative, such as graphene oxide is also found attractive as a promising reinforcing phase material in the fabrication process of polymer composites.^[124] And several studies have reported that graphene oxide (GO) has a good effect on the performance of epoxy composites.^[125–127] However, considering the potential effects of nanofillers on modifying the properties of polymer matrices, Xue et al.^[101] developed epoxy nanocomposites reinforced with in situ functionalized nano graphene oxide using a facile wet mixing and solvent evaporation techniques. The GO was functionalized with 3',4'-epoxycyclohexylmethyl-3,4-epoxycyclohexanecarboxylate (GO-2021P). The surface modification of the GO result to its thermal stable and hence change its nature from hydrophilic to hydrophobic. Thus the effects of the surface functionalization on the morphology of GO contents, its dispersion in the epoxy matrix, thermal and mechanical

properties of the composites were examined. From the study, analyzing the nanocomposites microstructure using digital microscope and transition electron microscope (TEM), it was reported that grafting of GO with 2021P, improved its dispersion and as such the exfoliation status of the GO and interfacial interaction between the epoxy matrix and GO were enhanced. The results also indicated that the tensile strength (62.3 MPa) and Young's modulus (3.02 GPa) of epoxy nanocomposites reinforced with 1.0 wt % GO-2021P increased by 34% and 25.9%, respectively, when compared to neat epoxy (46.5 MPa and 2.40 GPa) and 1.0 wt% unmodified GO/epoxy nanocomposite (52.4 MPa and 2.64 GPa). Further, the glass transition temperature and thermal stability of the reinforced nanocomposite were improved. The outcome of the study shows that the properties of graphene based polymeric nanocomposites greatly depends on the dispersion of graphene oxide. Furthermore, in order to employed epoxy matrix as lubricating material, Bao et al.^[102] modified epoxy resin with polyetheramine-functionalized graphene oxide so as to improve its tribological properties. The friction, mechanical, and thermal properties of the composites were investigated at different concentrations of functionalized-GO fillers (0.1 to 0.4 wt %). The tribological behavior of the epoxy nanocomposites were fully determined against GCr15 steel ball with a surface hardness of 63HRC on a ball-on-disc reciprocating under different loading conditions. The results showed that the incorporation of the functionalized-GO contents into the epoxy resin reduced its friction coefficient and wear rate. Where, the optimum tribological performance was obtained at 0.2 wt% functionalized-GO loading. Simultaneously, the modified GO, also improved the thermal, and mechanical properties of the composites, owing to the observed disparity and strong interfacial bonding in the matrix. Again, the reported outstanding lubrication and wear resistance properties of the composites could be attributed to the good interaction of the composites and transfer film. However, the findings revealed a prospect to the practical application of the graphene oxide and solve wear related mechanical failures of epoxy resin. In a certain study, it was observed that thermosetting resin based on bisphenol epoxy usually exhibits high rigidity and brittleness, hence limits its wide potential applications. Regards to this information, Wu et al.^[103] fabricated a novel tertiary amine (NC-514-DEA), which contains cardanol-based epoxy resin via reaction of diethanolamine (DEA) with cardanol epoxy resin (NC-514). Further, the author prepared NC-514-DEA modified- graphene oxide (GOND) and was employed as a reactive nanofillers reinforcement phase to develop epoxy nanocomposites. Meanwhile, the evaluation was on the mechanical and tribological properties. In comparing the obtained result of the virgin epoxy resin, the nanocomposites with

0.5 wt% GOND exhibited a reduced coefficient of friction from 0.567 to 0.408 under dry condition against steel ball, which was used as the friction pair. And its fracture toughness was increased by 10%, hence demonstrating the optimal performance over other samples. Here, the enhanced wear resistance and mechanical properties of the composites could be ascribed to the synergistic influence of NC-514-DEA and GO, which contributed in hindering the growth and propagation of cracks by improving the interfacial interaction and stress distribution within the nanocomposites. On the other hands, the reactive bio-based epoxy grafted on the graphene oxide can improved the interface bonding between the epoxy matrix and the filler. Accordingly, the author synthesis process has actually provides a novel means of designing epoxy nanocomposites materials for mechanical and tribological applications. In addition, studies conducted by^[104–107] revealed more on improving the thermal, mechanical, and wear performance of epoxy matrix with graphene hybrid, silica, titania, and graphene oxide. And such findings were presented in Table 1.

1.4. Challenges facing epoxy reinforced nanocomposites for mechanical and tribological applications

In the fabrication of polymer composites for mechanical friction applications, epoxy reinforced nanocomposites have gained wide attention as a favorable candidate material for such application. From the review literature, several studies have been conducted on improving the properties of epoxy matrix nanocomposites using nanoinorganic and carbon based nanofillers, such as Al₂O₃, TiO₂, SiO₂, SiC, MoS₂, Si₃N₄, ZnO, ZrO₂, CNTs, GNP, GO and so on for mechanical, friction, and wear applications as can be seen in Table 1. However, epoxy matrix nanocomposites were still noticed to be facing some challenges, such as mechanical properties degradations caused by particle agglomeration,^[38,98,120] which have detrimentally affects the toughness and tribological characteristics of the nanocomposites.^[128] Notwithstanding the various efforts, which has been made and the advancement of enhancing the mechanical, thermal stability, and wear behavior of epoxy nanocomposites for tribological applications, there is still a need to eliminate the occurrence of agglomeration during the fabrication process. Several researches have involved surface modification of the nanofillers for their good dispersion and distribution in the epoxy matrix nanocomposites as to avoid particle agglomeration via ultrasonication assisting process. But that could not put a stop to the aforementioned issues on critical nanofillers contents particularly on the inorganic fillers.^[86] However, there is need for future studies on improving the mechanical and tribological properties of

reinforced epoxy nanocomposites with negligible agglomeration. In considering the cost effectiveness and improved interfacial interaction of polymer composites prepared employing injection molding technique, the reported agglomeration in reinforced epoxy nanocomposites, which has affected its properties, can be eliminated. Besides, the development of polymer composites with injection molding technique usually results to near zero void content. Hence contribute to mechanical properties improvement of the composites, especially its fracture toughness.^[129,130] Again, optimizing the processing parameters and incorporation of well functionalized nanofillers in the epoxy matrix network to develop epoxy nanocomposites using Taguchi design of experiment and injection molding method could be a breakthrough in this area of applications. Moreover, injection molding is a low cost and time saving method of processing polymer composites. In addition, introduction of nanofillers, such as nano-boron free glass fiber and niobium carbide into epoxy based composites could be a way forward in developing a new material for thermal, mechanical and tribological applications. This is because niobium carbide (NbC) has reportedly been employed as a high potential material for wear protection and tribological applications,^[131] which is non toxic to human health. Furthermore, the low density of NbC has eventually attributed to its advantageous dynamic performance.^[132] More so, nano boron free glass fiber has impressive mechanical, thermal, and good corrosion resistance properties^[133] and as such could be a good candidate reinforcement material in producing epoxy nanocomposites. Therefore, this review recommends the adoption of nano-NbC, and nano-boron free glass fiber as a reinforcement phase in epoxy composites. Hence a point for future study, which could contribute and address most issues by improving the epoxy composites properties for thermal, mechanical, and tribological applications.

2. Conclusion

The study has reviewed the numerous means of improving the properties of epoxy reinforced nanocomposites for mechanical and tribological applications. From the review study, it is quite clear that epoxy nanocomposites remains a considerable material for fabricating friction moving parts, which can be used in machine, automobile, aerospace, and marine industries. However, this current review article has been able to summarize the previous research conducted and recent advances on the influence of nano-inorganic and carbon based nanofillers on the thermal, mechanical, and tribological properties of epoxy matrix for mechanical friction and wear applications. It was observed that epoxy nanocomposites as a friction material for mechanical and tribological application still face some

challenges, such as agglomeration and porosity, which has reportedly leads to their mechanical properties degradation and as such affects their tribological performance. Various efforts have actually been made on reducing the friction coefficient of epoxy nanocomposites by improving their wear resistance under different condition, such as surface functionalization of the nanofillers using amino and silane coupling agent before their incorporation. However, the improvements of epoxy composites characteristics for mechanical, thermal, and tribological applications are still needed in order to maintain their utilization in this area of applications. As such the authors recommend further research on improving the processing and the properties of epoxy nanocomposites using injection molding technique. Also, the introduction of novel nano-NbC and nano-boron free glass fiber into the epoxy matrix with suitable optimization process using Taguchi design of experiment and injection molding technique can be a total breakthrough in the advancement of epoxy nanocomposites for tribology system application.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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