A review of mechanical and tribological behaviour of polymer composite materials

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Abstract. Composite materials are finding increased applications in many industrial applications. A nano-composite is a matrix to which nanosized particles have been incorporated to drastically improve the mechanical performance of the original material. The structural components produced using nano-composites will exhibit a high strength-to-weight ratio. The properties of nano-composites have caused researchers and industries to consider using this material in several fields. Polymer nanocomposites consists of a polymer material having nano-particles or nano-fillers dispersed in the polymer matrix which may be of different shapes with at least one of the dimensions less than 100nm. In this paper, comprehensive review of polymer nanocomposites was done majorly in three different areas. First, mechanical behaviour of polymer nanocomposites which focuses on the mechanical property evaluation such as tensile strength, impact strength and modulus of elasticity based on the different combination of filler materials and nanoparticle inclusion. Second, wear behavior of Polymer composite materials with respect to different impingement angles and variation of filler composition using different processing techniques. Third, tribological (Friction and Wear) behaviour of nanocomposites using various combination of nanoparticle inclusion and time. Finally, it summarized the challenges and prospects of polymer nanocomposites.

1. Introduction
Composite materials are macroscopic combination of two or more distinct materials having a recognizable interface between each other. Composites are not only preferred for their structural properties, but also used for their tribological, thermal and electrical properties to achieve desired properties for a given range of applications. Different types of polymers such as thermoplastics, thermostetting plastics and elastomers have been utilized for manufacturing polymer nanocomposites. Polymer nano-composites have superior properties if constructed properly.

Polymer matrix based nano-composites have generated a significant amount of attention in current research in the area of nanotechnology. The structural components produced using nano-composites will exhibit a high strength-to-weight ratio. For instance, an epoxy containing carbon nanotubes can be utilized to produce wind turbine cutting edges which results in a strong but light weight material, which in turn allows for longer windmill blades. Practically, these longer blades increase the amount of electricity generated by each wind turbine. A typical polymer nano-system is represented in Figure 1 where phase changes occurs from a natural nanoparticle which is added to polymer resin and then is further reinforced with fibers such as Glass, Carbon or Aramid fibers. Finally, it is cured using resin transfer molding (RTM) to a Polymer nanocomposite.
Nano-composite is fundamentally a multiphased solid material where one of the manufacturing phases has no less than one dimension under 100 nm. In recent years nano-reinforcements have received the greatest attention as a result of intense research and development. The main advantages of nanocomposites is its ability to achieve a desirable mechanical strength, toughness, increased wear resistance properties, as well as improved electrical and thermal conductivity by the addition of nanoparticles in as small a volume as 2-5 % of weight. Based on the matrix used, material composites are classified as Metal matrix composites, Polymer matrix composites and Ceramic matrix composites.

Polymer nano-composites are being increasingly used as engineering materials in which tribological properties are of considerable importance. Fillers, for example, glass, carbon and textile fibers are incorporated within numerous polymers to enhance their tribological properties. Nanoparticles such as carbon-nanotube, nano-clay, titanium oxide (TiO$_2$) and silicon carbide (SiC) are added in volumes of 2-5 % by weight which, in turn enhances the mechanical properties dramatically. The reduction in wear is due mainly to preferential load support or the load bearing capacity of the reinforcement components, by which the action of abrasive mechanisms to the wear of the materials is highly suppressed. Figure 2 shows microscopic images of nanotubes, nanographite, nanoclay and nanosilica for information and visualization of these microstructures.

When nano particles are embedded in the polymer, the resulting composite material is known as a polymer nano-composite. Polymer nano-composites consist of a polymeric material (e.g. Thermoplastics, thermosets or elastomers) having nano-particles or nano-fillers dispersed in the polymer matrix which may be of different shapes (e.g. fibers, spheroids or platelets) with at least one of the dimensions less than 100 nm. Figure 3 shows sample images for nanostructures of a DNA and carbon nanotube for reference.
2. Review of mechanical and wear behaviour

2.1 Mechanical behaviour of polymer composite materials

Various polymer materials, inclusive of fillers depending on the necessity of the applications are reviewed in this section. Polyester resin with glass fiber reinforced fillers have been employed to analyse the mechanical properties such as tensile strength, flexural strength and Young’s Modulus for single and multiple fibers by Ya-Jung Lee et al. [1]. They have generated a numerical model from the trial information generated which in the future could be utilized for accessing the mechanical properties of laminates delivered utilizing distinctive types of fibers without additionally tries. They have also concluded that GFRP laminates when subjected to flexural loading the stiffness after initial failure does not drop promptly but rather decays step by step. Sang-Young Kim et al. [2] have used vinyl ester epoxy resin and glass fiber reinforced fillers to analyse mechanical properties such as tensile strength, compressive strength and in-plane shear properties using the vacuum infusion process and hand layup process samples and found the vacuum infusion processed GFRP samples showed better mechanical properties than the hand layup technique due to handlayup’s technique increased porosity. Mouritz et al. [3] analysed the development of fibre-reinforced polymer composites in naval ships and submarines. The high strength to weight ratio finds applications in superstructures, decks, bulkheads, advanced mast systems, propellers etc. which were meant to reduce weight and in turn increases the speed and decreases fuel costs in the long run, as well as contributes to corrosion resistance and less maintenance costs. Selvaraju et al. [4] analysed the application of Aramid fiber reinforced polymer (CFRP) and glass fiber reinforced Polymer (GFRP) in marine applications such as naval patrol boats, submarine diesel storage tanks, lube tanks, utility tanks, low pressure pipes, cable ladders and trays with the intention of reducing weight, improving corrosion resistance and increasing the strength to weight ratio. Vallbo [5] has analysed the effects of the mechanical properties with
manufactured transport containing vinyl ester matrix and polyvinyl chloride (PVC) as a core material with carbon fibre reinforcement. This research found improvement in the mechanical properties, electrical properties, as well as lighter in weight, which in turn will reduce fuel consumption, thus being more environmentally friendly and finally having an increased payload.

Chalmers [6] studied the different types of resins such as polyester resins, vinyl ester and epoxy resin with different combinations of reinforcements such as E-glass, carbon and aramid fiber to reduce the stiffness, reduced maintenance load and manufacturing costs. Nagalingam et al. [7] conducted an analysis of different combinations of polyester resin, fiber and nano-clay (MMT) with varying percentages of combinations and observed the ultimate tensile strength decreased with an increase in the percentage of nano-clay and at the same time impact strength increased with the increase in the percentage of nano-clay.

Isao Kimpara [8] has studied the different composite materials used in marine construction such as GFRP, CFRP, AFRP and hybrid composite (FRP with two or more different type of fibers) materials with their current and potential applications. The research concluded that GFRP has been mainly utilized in the marine environment with the key considerations; reduction in weight, increased speed of the boat with an improvement in the mechanical strength and dynamic strength such as creep, impact and fatigue. Md Ekramul Islam et al. [9] concluded in their study FRP material was mostly utilised for marine applications and conducted experimental analysis using carbon fiber reinforced epoxy composites, which was modified with 2 % by weight of Montmorillonite (MMT) nanoclay and 0.3 % by weight of multi-walled carbon nanotubes (MWCNTs). The results were compared with unmodified carbon/epoxy composites and found that reinforcement with both nanoparticles significantly improved the mechanical and thermo-mechanical properties of carbon fiber reinforced (CFRP) composites. Anbusagar N.R.R et al. [10] determined FRP and Sandwich FRP has been mostly used in the marine sector and experimental studies were done with different combinations of FRP and sandwich FRP modified with Montmorillonite (MMT) nano-clay by the hand lay-up technique. It was observed that tensile strength and impact strength were significantly increased over the range of nanoclay loading. SEM images showed the adhesion of glass fibers to the polyester matrix was also greatly increased with an increase in the nanoclay content.

2.2 Wear of Polymer Composite Materials

Law Mei Lin et al. [11] conducted an experimental study using epoxy resin and recycled carbon fiber, which was obtained from two conditions, as received and cryogenic treated condition. The tribological properties including the wear rate and the coefficient of friction were taken at different time intervals for both combinations and found the coefficient of friction decreased and wear resistance improved in the treated carbon fiber with epoxy resin when compared to the as received condition. Shakuntala Ojha et al. [12] studied the wear behaviour of both raw and carbon black wood apple shell particles filled with epoxy resin. It was found the carbon black particulate composites showed a lower wear rate as compared to the raw particulate composite. The effect of wood apple shell particle concentrations with different impingement angles of 30, 45, 60 and 90° and at a constant impact velocity of 48 m/s was observed and found the maximum erosion rate occurred at 60° impingement angle. The minimum erosion rate occurred for carbon black composite at 20 wt% as compared to raw 10 wt% of filler composite.

Gai Zhao et al. [13] analysed friction and wear of polyimides reinforced with carbon, glass and aramid fibers. The research showed reinforcement improves the tribological properties of composites and the best performance was achieved by inorganic fiber reinforced composites compared to glass fiber reinforcement due to the effective load sharing between surfaces in contact. Anu Gupta et al. [14] conducted research using epoxy resin reinforced with relatively inexpensive bamboo fibers to
determine the mechanical and erosion behaviour of epoxy composites. Fiber composition ranged from 0-40% with increments of 10% by weight. The results demonstrated the erosion wear rate improved quite significantly by the addition of bamboo fibers and mechanical properties, such as tensile strength shown maximum value at 40 wt%, flexural strength and impact strength increased with 0-20% inclusion of fibers. The test results have also shown decrease in properties with 30% inclusion of fibers, furthermore mechanical properties increased above 30% inclusion of bamboo fiber reinforcement. Refer graphs in Figure 4, 5 and 6 for details.

Mohit Sharma et al. [15] conducted a study using polyethersulfone (PES) reinforced with carbon fabric. A comparison was made between carbon fibers treated with cold remote nitrogen and untreated carbon fibers reinforced with PES. It was observed that the plasma treatment of carbon fabric increased the fiber-matrix adhesion and enhanced the coefficient of friction and wear resistance properties when compared to untreated fibers. There was a correlation between the tribo-performance with molecular weight and tensile strength. Suresha et al. [16] carried out a study using epoxy resin with reinforced E-Glass and graphite filled epoxy composites. The wear resistance was observed for three different combinations and it was found that epoxy with E-Glass filler reduced the wear properties and the epoxy composites with E-Glass and graphite showed the least wear when compared with neat epoxy. The mechanical properties, such as tensile strength, tensile modulus and hardness increased with the addition of E-Glass and graphite filled composites.

Figure 4. Effect on tensile and flexural strength with inclusion of bamboo fiber [14]

Figure 5. Effect on Impact strength of composites with inclusion of bamboo fiber [14]
Figure 6. Effect on the erosion wear rate of composites with Impingement angle [14]

Mihail Botan et al. [17] analysed the tribological performance of polybutylene terephthalate (PBT) with an aramid fiber composite (10 % by weight) to measure the wear and frictional properties under different loads and velocities. The analysis showed the presence of aramid fibers increases the friction coefficient gradually with the applied load and the sliding speed. Jian [18] studied the friction and wear performance of polyvinylidene fluoride (PVDF) reinforced with carbon fibers of varying percentages ranging from 0, 10, 20 and 30 % under varying loads. The coefficient of friction and wear increased with the increase of load and the optimal wear resistance was obtained with a carbon fibre content of 20 %. All filled PVDF composites exhibited improved tribological properties. Singha et al. [19] utilized natural fibers of Hibiscus Sabdariffa with phenol-formaldehyde resin matrix to analyze the tensile strength, flexural strength, compressive strength and wear resistance properties. The results revealed that the mechanical and wear resistance properties increased up to 30 % with fiber reinforcement and then tended to decrease beyond that loading. Reza Arjmandi et al. [20] used the natural fiber of rice husks with different polymer matrices such as PE, PP, PVC and PLA to form polymer composites. The results revealed that inclusion of rise husk resulted in the reduction of tensile strength and the addition of other fillers such as MMT increased the mechanical properties. Also noted was that rice husks combined with PE showed the best results when compared to the other composites.

Pravuram Panda et al. [31] explored the mechanical and erosion wear of E-glass fiber reinforced 50 % by weight in epoxy resin. It was further reinforced with aluminum nitride of different percentages by weight (5, 10 and 15 %) using the hand lay-up technique. The results indicated that as the hardness increases with an increase in the percentage of aluminum nitride which is maximum at 15% inclusion, the tensile strength decreased which was contradictory. The maximum wear rate was observed at 60° impingement angle. Refer graphs 7 and 8 for details. J. Sudeepan et al. [32] utilized Acrylonitrile-butadiene-styrene(ABS) filled with micrometer sized titanium di-oxide of varying concentrations ranging from 5, 10 and 15 % by weight as filler content to determine the tribological (friction and wear) behavior of the polymer composite. It was also noted that the optimal conditions for the coefficient of friction was found to be with 15 % filler content and a specific wear rate with 10 % filler content. Hiral H Parikh et al. [33] has carried out a literature review for different fiber reinforced polymer composites and studied the effects of both material parameters such as type of filler, fiber length, filler content, fiber orientation and the operating parameters such as load, sliding distance,
sliding velocity and temperature. Both parameters have a significant effect on the tribological properties of composite materials.

2.3 Tribological (Friction and Wear) behaviour of Nanocomposites

Tribology is related to the study of interacting surfaces in relative motion which in turn applies the principles of friction, lubrication and wear. Nano particles added to polymers tend to be effective in reducing the wear rate and the coefficient of friction of composites. Chun et al. [21] have conducted an analysis to study the mechanical behaviour of nanoclay in epoxy composites with varying percentages of nanoclay ranging from 0 to 4 % by weight. It was observed that wear resistance and hardness of nanoclay composites increased with the increasing percentage of nanoclay but this also depends on the degree of agglomeration of nanoclay clusters in the Nanoclay/Epoxy composites. Bhuyan et al. [22] studied the tribological behaviour of bio-based nanocomposites using soybean oil and functionalized organoclay (VMMT) with varying percentages of VMMT from 0, 1 and 5 %. The study revealed that the addition of clay of 1 % by weight resulted in a superior wear performance compared to results with lower and higher clay modifications. Wang et al. [23] have conducted a study to analyse the hardness and tribological behaviour of Polyacrylonitrile-methylmethacrylate-carbon nanotubes (AMMA-CNT) which are co-polymer nanocomposites, with varying compositions of CNT ranging from 0 to 3 % by weight in increments of 0.5 % by weight. The results indicated that nanocomposites with a 1.5 % CNT addition exhibited the lowest wear rate of $5.82 \times 10^{-4}$ mm$^3$ N$^{-1}$ m$^{-1}$ and a lower coefficient of friction of 0.36. The significant improvement in tribological properties of AMMA-CNT composites have also attributed to excellent improvement in mechanical properties of composites.

Jawahar et al. [24] conducted an analysis using the pristine polyester, polyester with conventional clay-filled composite and polyester reinforced with nanoclay to study the flexural strength, flexural modulus, wear rate and coefficient of friction. It was found the nanocomposites possessed an improvement in flexural properties up to 20 % and wear properties up to 85 % when compared to the conventional clay-filled composites and pristine polyester. Lingaraju et al. [25] analysed the mechanical and tribological properties of polymer hybrid composites including nano particles. Results of the experiments have shown that the inclusion of nanoparticles such as silica and clay to the glass
fiber reinforcement epoxy composite with varying percentages of 0 to 3 % by weight improved the mechanical properties such as tensile strength, impact strength, hardness and wear rate when compared to the pure composite material.

Kadhim et al. [26] conducted an analysis of the tribological properties using an Epoxy resin/Unsaturated polymer resin (80 % vol. /20 % vol.) reinforced with Nano-SiC and ultrafine graphite particles with varying percentages of SiC. Results indicated that the wear rate was higher for the blended resin when compared to the Nano-SiC composite. In addition, the wear and friction coefficient decreases with an increase in time and the percentage of Nano-SiC. Galetz et al. [27] conducted an analysis utilizing ultra-high molecular weight polyethylene (UHMWPE) reinforced with Carbon nanofibre (CNF) with varying percentages of CNF from 0, 5 and 10 % in weight. The test results revealed that the addition of nanofibers increased the mechanical properties such as modulus, yield stress and hardness. The wear rate of the composite material was reduced significantly from a 5 % inclusion of nanofibers although; an inclusion of 10 % nanofibers increased the wear rate.

Dong et al. [28] used polymethyl methacrylate/styrene and multiwall carbon nanotubes with varying composites of CNT ranging from 0-3 % with increments of 0.5 % and it was observed that the micro hardness increased with an increasing percentage of CNT and the tribological parameters such as friction coefficient and wear rate decreased with an increasing concentration of CNT. It was also noted that carbon nanotubes with 1.5 % CNT exhibited the highest wear resistance and the lowest friction coefficient. Zhang et al. [29] observed the wear resistance properties of epoxy fillers using short carbon fibers, graphite, Polytetrafluoroethylene (PTFE) and nano-TiO₂. The results indicated that each individual filler improves the wear resistance independently and it was also observed that the optimum wear properties was determined at 4-6 % nano-TiO₂ and the best wear resistance properties were achieved from nano-TiO₂ combined with conventional fillers.

Xin-Rui et al. [30] carried out an investigation on the friction and wear using different combinations of Polyimide (PI) with short carbon fibers (SCFs), micro SiO₂ and graphite particles. The results showed that incorporation of SCF and graphite particles to PI improved the tribological properties and the addition of SiO₂ to PI showed an adverse effect. The most effective results were observed with a combination of PI, SCF, graphite and micro SiO₂ particles.

3. Conclusion of literature review analysis

The careful review of published literature indicates that there has been no comprehensive analysis carried out so far and it is clear that further research on the mechanical and tribological behavior of polymer nano-composite materials is needed to investigate. Most of the research was carried out without the use of lubrications; therefore the use of lubrication in fabricating composite materials and the effect of lubrication on the wear rate [33] could be studied. Also it is rare to find the tribological properties of nano polymer composite materials having nano metal fibers with process optimization [18, 19, 22, 28 & 32]. The literature study is carried out to fill the gap in the literature, for the study of fiber reinforces polymer metal nano composites. Based on the literature study, the research gap is identified and they are presented as follows:

- Very limited mechanical property study has been carried out in fiber reinforced polymer metal nano composites so far and especially for carbon fiber reinforced polymer-SiC composites.
- Literature review indicated that the polymer composites with glass fiber reinforcement have a higher erosion rate than those without glass [33], which can reveal the need to use carbon fibers as reinforcement in this research.
Epoxy resin LY556 and hardener HY951 are used so far in the previous researches for making composites. New grade is used in this study as a difference in epoxy resin as B-11 (3101) and hardener as K-6 (5205).

Very limited study is carried out on the modeling of tribological properties for fiber reinforced polymer-metal nano composites.

The review of literature indicated that the application oriented studies for the fiber reinforced polymer-metal nano composites are very few.

Further the review of literature indicated that the optimization studies carried out on the fiber reinforced polymer-metal nano composites are very limited.

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