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A review on mechanical and wear properties of fiber-reinforced thermoset composites with ceramic and lubricating fillers

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ABSTRACT

The need for exploring the mechanical and wear behavior of thermoset polymers and their composites is found to be ever-increasing, owing to their usage in an enormous number of engineering applications. This article briefs recent studies and inferences drawn on mechanical and tribological (wear and friction) behavior and several other associated factors that govern the properties of polymer-based composites. In addition to primary reinforcements, a wide range of secondary fillers are being reinforced in polymers to enhance mechanical and wear performance. Glass, Carbon, and Kevlar are widely used primary reinforcements in polymers along with various secondary reinforcements like SiC, Si_3N_4, Al_2O_3, MoS_2, WS_2 TiO_2, SiO_2, ZrO_2, MbO_2, ZnS, $CaCO_3$, CaO, $MgCO_3$, Ta/NbC, MgO, TiC, polytetrafluoroethylene (PTFE), graphite, and hexagonal boron nitride. A detailed review of research carried out by scientists to correlate the effect of secondary reinforcements on the mechanical and tribological performance of polymer composites is documented in the present article. The impact of the geometry of primary reinforcements along with varying particle size and volume fraction of secondary reinforcements is discussed in the present paper. Surface modification, which is considered as a substantial solution for delamination by many researchers, is discussed.

Selection and peer-review under responsibility of the scientific committee of the 3rd International Conference on Materials, Manufacturing and Modelling.

1. Introduction

Recent times have witnessed extensive research in the field of materials, and most of it was focused on developing composite materials. Polymer Matrix Composites (PMCs) are promising materials for many engineering applications due to their superior properties like high specific strength, specific stiffness, corrosion resistance, self-lubricating properties, excellent chemical stability, electrical insulating properties, and wear resistance [1]. PMCs find their applications in the aerospace, marine industry and sports industries. Also, other applications include the toy industry, coal handling equipment's in power plants, bearings, gear pumps, cosmetics, and medical devices.

Polymers are categorized as thermosets (epoxy, phenol–formaldehyde resins, polyester, and polyurethanes) and thermoplastics (PEEK, polyamide, nylon). Thermoset resins have high modulus, strength, durability, high dimensional stability, high-stiffness, good resistance to creep, low densities, high electrical, and thermal insulating properties as compared to thermoplastics [2]. Near net-shaped products can be manufactured using PMCs [3]. A wide range of synthetic fibers like carbon, glass, boron, aramid, and natural fibers are reinforced in the polymer matrix to form fiber-reinforced polymer (FRPs) composites [4]. Among the available synthetic fibers, glass and carbon fibers are widely used in aerospace and automotive sectors due to their enhanced properties like toughness, medium modulus, strength, and stability. Glass filaments are widely used to fortify plastics because of their great mechanical properties and ease of fabrication [5]. Fabrication methods like hand layup [6], pultrusion [7], compression molding [8], vacuum infusion molding [9], and vacuum-assisted resin transfer molding (VARTM) [1011] are widely used by most researchers to develop PMCs.

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1.1. Fillers

The addition of fillers in PMCs will enhance the mechanical and tribological properties. Fillers can be used in various forms such as particles, nanofillers, articular and fibrous fillers as shown in Fig. 1. Among all the available fillers, particulate fillers are more effective in increasing the hardness and stiffness of PMCs [12,13].

The addition of fillers will improve the stiffness of PMCs and are economically viable [14]. Silica fillers when added to PMCs improve the electrical, mechanical, thermal, and tribological properties of PMCs [15]. Kishore et al. [16] observed that introducing secondary reinforcements like ceramic fillers enhanced the mechanical properties. B Suresha et al. [17] used the SiC whiskers as fillers in CFRP and observed that an increase in tensile modulus by 15% flexural strength up to 8% compared to unfilled CFRP. The aspect ratio of fillers plays a significant role in the performance of PMCs [18]. Min Hyung Cho et al. [19] studied the effects of three solid lubricants graphite, Sb_2S_3, and MoS_2 on tribological behavior for automotive brake applications. The solid lubricant fillers improved frictional behavior thereby reducing coefficient of friction (CoF).

1.2. Epoxy

Epoxy resin is one of the most adaptable classes of thermoset, with a wide scope of utilization in the fields such as composites, electrical devices, paints, coating, adhesive, and constructions. Epoxy resins mixed with a hardener with suitable proportions to get solid material. Unmodified epoxy resins have certain drawbacks like high thickness, expensive, and lack of flexibility in the manufacturing process. Diluents, fillers, and additives are added to resins to improve their properties [20]. Epoxy resin has been remarkably important to the engineering field for many years due to exceptionally good mechanical, thermal, and electrical properties. Among various available fillers, ceramic, and solid lubricating fillers enhance the mechanical and tribological properties of epoxy composites [21].

2. Effect of fibre geometry on mechanical and wear properties

The reinforcements in PMCs are particles, fibers, whiskers, and lamellae. The composite's properties not only depend on the material type, but also the size, shape, volume, and distribution of the material. The reinforcement bears the majority (70 to 90%) of the load applied on the composite. FRPs have better strength and durability compared to the base material. The fibers are mainly classified as synthetic and natural fibers. In recent years, the interests have been shifted to the production of natural fiber composites due to their advantages over synthetic fibers. The natural fibers are biodegradable and non-abrasive in nature, also low-cost, low-density, and highly specific strength. With additional modifications, natural fibers can be directly reinforced into PMCs. However, some drawbacks, such as hydrophobic nature with matrix, processing, and poor resistance to moisture, significantly reduce the scope for the use of natural fibers in polymer reinforcement [22].

The use of various geometric style helps to improve the mechanical and tribological properties. A continuous fiber has a high length-to-diameter proportion. There are two significant kinds of textures available in the composites industry; woven textures and nonwoven textures. Woven textures are utilized in trailers, holders, scow covers, water tower edges, and in other marine wet layup applications. These textures are woven yarns, rovings, or tows in tangle structure in a single layer. Various weave styles of fiber are shown in Fig. 2. Woven textures are made by utilizing at least two arrangements of strands joined at the right edges to one another. One is known as the twist, and the other is known as the weft course. Woven textures are commonly strong and are delivered on looms in a wide variety of loads, weaves, and widths.

Alok Hegde et al. [23] studied the effect of orientation of fiber on FRPs. It is understood that the FRPs exhibit higher strength and stiffness in the longitudinal direction as compared to transverse directions. Bijwe et al.[24] studied the influence of the orientation of fabric on abrasive wear, the performance of wear resistance shown better in the orientation of fiber normal to sliding plane as compared to the parallel to sliding plane. Vishwanath et al. [25] studied the glass fabric (plain weave, woven roving, and satin weave) reinforced in modified phenolic resin and they revealed that woven roving fabric composite shows better tensile, flexural, interlaminar shear, and impact strength. Also, it was concluded that plain weave fabric composite having a greater crimp shows better wear resistance and a lower coefficient of friction as compared to the satin weave and woven roving. Jayashree Bijwe et al. [26] studied the effect of fiber geometry of glass fabric (plain, weave, and the twill) reinforced in the polyetherimide (PEI) matrix with additional fillers polytetrafluoroethylene (PTFE) and Cu powder. It was concluded that plain weave glass fabric shows better wear resistance, three times higher the neat PEI, and a low coefficient of friction (50% reduction compared to neat PEI) in the various loading conditions. Twill weave glass fabric composites exhibit lower performance in wear while woven fabric shows some improvements in wear properties at higher loads. M Cirino et al. [27] studied the orientation effect on wear performances of carbon-fiber-reinforced polyetheretherketone (PEEK) and continuous aramid fiber reinforced epoxy composites. When the fibre is orientated normal to the sliding surface it shows the minimum wear rate and did not show many changes up to a variation about

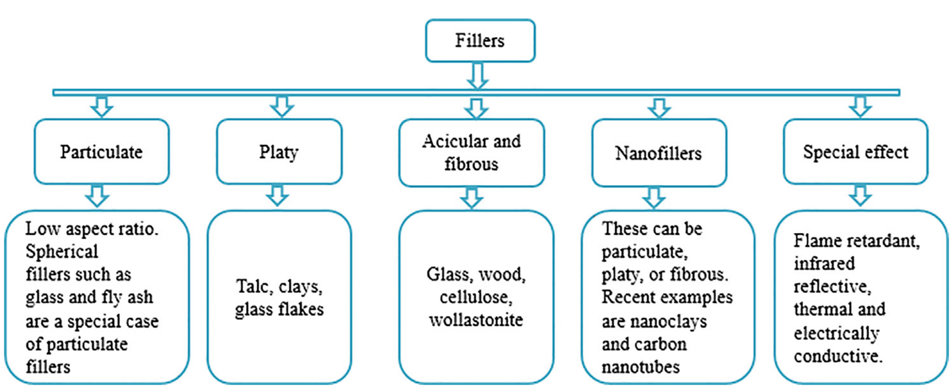

Fig. 1. Types of Fillers.

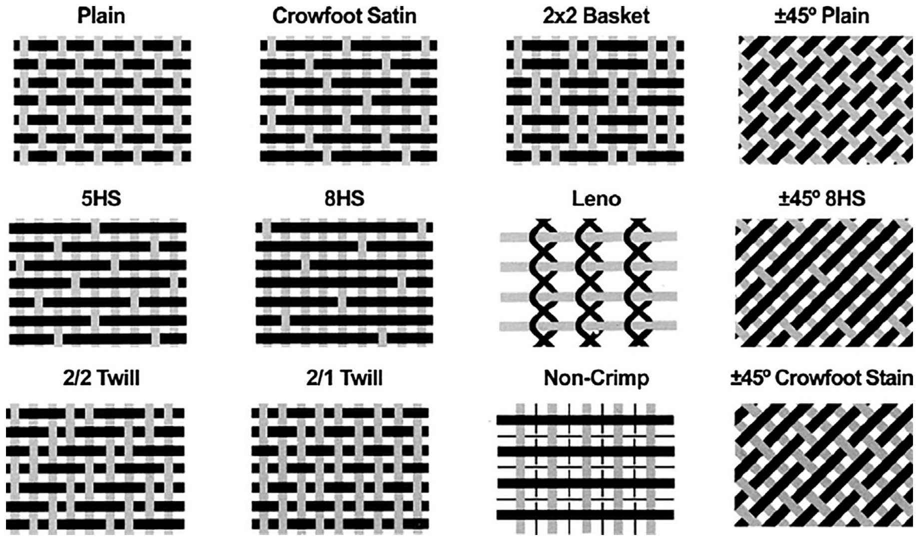

Fig. 2. Various weave styles for fabrics [1].

30^0 to the normal orientation. It was inferred from the above discussion that fibre geometry plays a significant role in altering mechanical and tribological properties.

3. Effect of fillers

The filler is typically added in composites to enhance the mechanical and tribological properties. Fillers reinforced in small weight percent can improve the properties. Fillers have been introduced massively since the beginning of polymers to decrease cost. Nowadays fillers are more regularly joined into PMCs to improve their mechanical properties, instead of cost purposes. Many researchers summarised that the mechanical behavior and wear resistance of PMCs are significantly improved due to the small size of the fillers contribute to a very large interface region in the composites. The interface controls the contact level between the filler and the polymer and then regulates the characteristics. J. Bijwe et al. [28] studied the influence of fillers and fiber reinforcement in PEI. They reported that the specific wear rate decreases with an increase in load. Also, they concluded that the abrasive wear increased with the fillers such as graphite, PTFE, and MoS_2, but shown a decreased trend for bronze-filled polytetrafluoroethylene. Rashmi et al. [29] studied the dry sliding wear behavior of epoxy with organo-modified montmorillonite (OMMT) filled nanocomposites. It was reported that the wear rate mainly depends on the sliding distance parameter, and the highest wear resistance was observed in 5 wt%. OMMT nanofiller composite. R. Baptista et al., [30] studied and reported the effect of graphite-filled CFRP composite on mechanical and tribological performance. High elastic modulus and high wear resistance was observed for the high amount (0 to 11.5 wt%) of graphite content due to lubricating action. Xing et al., [31] fabricated the epoxy matrix composites filled with spherical silica particles at various weight percentages (0.5–4.0 wt%). The greater wear resistance was observed due to the smaller-sized filler in the resulted composites. The fillers play a major role in improving the mechanical and tribological properties, and it has proved by various other researchers [32,33].

4. Effect of size of fillers

The mechanical and tribological characteristics of filled particulate composites depend on their size, shape, surface, and distribution. The size and angularity of particles play an important role in improving the properties of PMCs. High aspect ratio fillers have a high ratio of length to diameter. Whiskers are very small single crystals with an exceptionally large aspect ratio. As a result of their small scale and aspect ratio responsible for the strength of PMCs. Despite these high strengths, whiskers are not commonly used for reinforcement as they are very costly. Besides, the incorporation of whiskers into a matrix is complicated and sometimes impractical. Graphite, SiC, Si_3N_4, and Al_2O_3 are the filler materials that can produce in the form of whisker [34]. The effect of the size of the particle is significantly decreased by scaling the particle size down to a nanometer scale and optimum use of nanoparticles typically less than 1 vol% [35]. Recent developments in nanotechnology and improvements in processing methods have allowed nanoparticles synthesis and their use in polymer matrix materials for nanocomposite manufacturing. Nanoparticles have a very broad interaction between their surface and volume and are also considered to be interface-dominated materials. This is highly difficult to spread nanoparticles evenly due to their limited sizes. Agglomeration of nanoparticles usually occurs in the manufacturing stage. For large wt. % of fillers, this issue is even more complicated. Low nanofiller loading (1–4 vol%) is therefore stated to have resulted in substantial improvements in PMCs performance. A wide variety of solid organic and inorganic, natural, or synthetic particulates are commercially already used as reinforcing fillers in polymeric composites. Chen [36] studied the effect of modified graphite nano-plates on CFRPs and revealed that the inclusion of fillers, enhances the mechanical properties of the CFRPs. M.S. Senthil Kumar et al.,[37] studied the effect of nano clay reinforced in glass–epoxy composites. It was concluded that experimental results showed the least wear and coefficient of friction (CoF). Fiber effect contribution was less on wear and friction coefficient as compared to without fiber nano clay epoxy composites and it was revealed by analysis of variance.

5. Effect of volume fraction

Primary reinforcement fiber and secondary reinforcement fillers are used to improve the mechanical and tribological properties of the PMCs. Most fillers have a beneficial effect on mechanical properties that are well established in the literature. The effect of volume fraction of fiber and fillers are greatly influencing the mechanical and tribological properties of PMCs. The optimum fiber volume fraction is 60 wt%, and fillers up to 15 wt% will give enhanced mechanical and wear properties. Manjunath et al. [7] shown that the 10 wt% (combined alumina, silica, and alumina trihydrate) of filled glass fiber-enhanced epoxy composite has increased its tensile, flexural, and impact strength by 9, 20, and 28%, in comparison with the unfilled composites. Yuanxin Zhou et al. [10] studied the epoxy filled with 2 wt% carbon nanofiber (CNF) used with satin-woven carbon fabrics in a VARTM process. The viability of CNF, in addition to the mechanical properties of the composite, was evaluated through flexural, tensile, and fatigue tests. In contrast to the composite without CNF, the tensile and flexural strengths increased by 11 and 22.3% respectively. Similar observations were also observed by the other author for the GFRP composites [38]. Cirino et al. [27,39] studied the behavior of abrasive wear on various types of continuous fiber-reinforced in PEEK and reported a decreased wear rate as the content of fiber was increased. The three-body abrasive wear behavior of short E-glass reinforced polyester composites was documented by Chand et al. [40]. They recorded that the composite exhibited a better wear resistance for the high wt.% of glass fiber. E- glass fiber 45 wt% reinforced composite shows 9.7% improvement in tensile strength compared with 40 wt% of fiber. Zhou et al. [10] studied the mechanical properties of carbon nanofiber (CNF) filled CFRP, tensile strength increased to 11% and modulus increased to 2% for inclusion of 2 wt% of CNF. Flexural strength increased to 22.3%, and modulus increased to 3% for 2 wt% of CNF.

6. Effect of hybridizing on mechanical and wear properties

Improvement of mechanical and tribological performance of PMCs can be accomplished by adding one or more secondary reinforcing fillers. The fillers exhibited high hardness, strength, and efficient lubrication effect [41]. The wide variety of different fiber and matrix materials makes the design of composites for different types of applications with a special combination of properties. The understanding of the wear behavior of FRPs is a complex activity. It depends on the various parameters such as fibers, matrix materials, fiber–matrix adhesion, fiber volume fraction, and the orientation of fibers [34].

Several studies have been published on PMCs that are subjected to abrasive and adhesive wear. Abrasive wear of three bodies is often necessary for practical purposes in coal handling equipment, gear pumps for the handling of industrial liquids, and in agricultural machinery components. In wear performance analysis, the principal parameters like sliding speed (S), applied load (L), and sliding distance (D) were considered. Higher wear loss has been observed under elevated stress levels and sliding speed conditions [42]. Pujan Sarkar et al. [43] studied the effect of parameters such as L and S on friction and wear behavior of PMCs. It was reported that the friction coefficient is constant for all the load values and increases with the increase in the S. Wear loss increases in respect of the increase in L and S for all the conditions.

Ravindranadh Bobbili and V Madhu [44] studied the wear behavior of multi-walled carbon nanotubes (MWCNT) filled in epoxy and also added to glass–epoxy composite to understand the specific wear rate, friction behavior with the controlling factors such as filler loading, S, L, and D by using design of experiments and ANOVA. It was concluded that filler percentage is the predominant factor concerning specific wear rate and friction coefficient. The specific wear rate decreases with an increase in the loading rate of fillers. F. Su et al. [45] studied the effects of Al_2O_3 and Si_3N_4 on carbon fiber reinforced phenolic composites. Incorporation of the fillers caused a significant decrease in the wear rates and Al_2O_3 was superior to Si_3N_4 in terms of the ability to increase the wear resistance.

K M Subbaya et al. [46] studied the hardness and abrasive wear performance of CFRP reinforced silane-treated SiC. Hardness increased to 8% with 10 wt% filler and abrasive wear resistance increased with 10 wt% filler. Based on ANOVA results, they concluded that filler content is the most significant factor, about 70% as compared to the grit size of abrasive paper, abrading distance, and load. N Mohan et al. [11] studied the wear performance at a higher temperature of GFRP reinforced Tantalum Niobium Carbide (Ta/NbC) as fillers. For the sliding wear, load and temperature was the predominant factor in the wear loss, lowest wear loss was reported for filled composite and highest for the unfilled composite at the highest temperature (120^0c).

The effect of secondary reinforcement on mechanical properties (hardness, tensile, and flexural strength) and tribological properties (wear and CoF) are summarized and listed in table 1. It was concluded from the literature review that by using the secondary reinforcements as ceramics and strong lubricating fillers, there is an improvement in the mechanical and tribological properties.

7. Surface treatment

Surface modifiers are commonly used to enhance the bonding between the reinforcement and matrix. For the fillers, two types of modifiers can be used such as non-coupling and coupling. The most popular coupling agents are silane and fatty acids. Some fibers have lower surface energy and surface area, due to this, the weak cohesive force occurs between fibers and matrix, and this leads to deteriorating the properties of PMCs. Surface modification is the only solution for debonding problems and can improve the wettability and improve the adherence of reinforcements. The classification of surface treatment methods for fibers is as shown in Fig. 3. To improve the strong adhering property of fiber- matrix, surface treatment methods are chemical method [68], plasma treatment method [69], and electrochemical method [70].

The surface modification of inorganic particles is an area of concern in the present day [71]. There are usually two ways to change inorganic particulate surfaces. The first is carried out with small molecules such as the silane binding agent, through the surface absorption. The second approach is based on grafting polymeric molecules by covalently binding the particles with the hydroxyl groups. Guang Shi et al. [72] studied the surface modification of Al_2O_3 with two different methods namely silane and graft polymerization. It was concluded that the graft polymerization is better than silane treatment for improving tribological efficiency than among the modifying techniques of nanoparticles used in this work. It was concluded that enhanced wear resistance was shown for the 0.24 vol% of alumina treated with graft polymerization as compared to silane treatment. Xinrui Zhang et al. [73] studied surface treatment by sol–gel technique on carbon fiber and their effects on the tribological properties of carbon fabric reinforced phenolic composites. The surface treatment to carbon fabric by the SiO_2 sol–gel technique results in the transfer of loads from the matrix to fiber effectively which gives the high wear resistance as compared to untreated composite. Alok K. Srivastava et al.; [74] studied the effect of oxidation treatment and graphene nanoplatelets coating on carbon fibers on the improvement of flexural strength of the resulting composite. A vacuum-assisted resin transfer molding technique was used to prepare the composites, and 0.4 wt% of graphene platelets coated composite shows a 20% increase in flexural modulus and flexural strength as compared to without coated specimen. Y. Z. Wan et al. [75] studied the effect of surface treatment and lubricating condition on tribological properties of 3D braided woven CFRP. The required specimens were prepared with the VARTM process. It was concluded that the coefficient of friction and the specific wear rate decreases

Table 1
Summary of mechanical and tribological properties of hybrid composites.

Sl. No.	Material			Manufacturing Method	Outcome				Reference
	Fiber	Matrix	Fillers		Tensile	Flexural	Hardness	Wear and Friction Coefficient	
1	Glass	Epoxy	SiO_2	Hand layup, Compression Moulding	Reduction in tensile strength was observed at a lower percentage (3%) of SiO_2, and an increase in strength up to 28.6% was found at higher reinforcement percentages (10%) of SiO_2	Increase in flexural strength by 10% at 3% SiO_2	Maximum hardness was found with an increasing weight percentage of SiO_2	Low specific wear rate and CoF was observed with an increase in wear load	[8,47,48]
2	Carbon	Epoxy	Al_2O_3 and MoS_2	Hand layup followed by a compression molding technique	Strength increased to 6% for Al_2O_3 composite and 17.4% for MoS_2, max strength and modulus was observed for 10 wt% filler composite compared to unfilled composite	Strength increased to 14% and 21% for Al_2O_3 and MoS_2 filled composite respectively. Flexural modulus increased to 17% and 40% for Al_2O_3 and MoS_2 filled composite respectively	Increased 8.2% with 10 wt% alumina filler and 9.5% with 10 wt% of MoS_2	Abrasive wear performance is greater in 10 wt% MoS_2 as compared to 10 wt% of Al_2O_3. Specific wear rate and coefficient of friction decrease with an increase in abrading distance. The coefficient of friction is influenced by MoS_2.	[49–51]
3	Glass	Epoxy	Al_2O_3	Dry hand layup	Strength and modulus increased to 38% for 10 wt% filler	Flexural strength 33% and modulus 78% increased for 10 wt% of filler loading.	Increased to 14% with 10 wt% filler	Abrasive wear less with 10 wt% filled composite; abrading distance have less influence compared grit size of SiC paper	[52,53]
4	Carbon	Epoxy	Organo modified montmorillonite	Hand layup followed by autoclave mold technique	Strength increased to 15.8% with 5 wt% filler	NA	Increased to 24.5% with 5 wt% filler	Three-body abrasive wear of 5 wt% filler specimen exhibited better abrasion resistance and specific wear rate decreases with an increase in abrading distance and load.	[54]
5	Glass	Epoxy	SiC	Hand layup	Strength increased 27.77% compared to unfilled composite	Strength increased to 32.9% compared to unfilled composite	Increased to 17.6% compared to unfilled composite	For sliding and abrasive wear, specific wear rate increases with an increase in applied load. For all abrading distances, the composite shown higher wear resistance but no effect of sliding distance on wear in dry sliding case.	[55–58]
6	Carbon	Epoxy	Graphite	Hand layup-Autoclave mold technique	Tensile strength increased 9% for the 10 wt% of a filler	Increases with increase in filler content	Increased to 3.2% as compared to unfilled composite	Sliding wear and abrasive wear of filled specimens show less wear loss as compared to unfilled composites, wear loss increases with an increase in load	[59–62]
7	Glass	Epoxy	Graphite	Hand layup	Strength increased to 11.6% & modulus increased to 16.6% compared to unfilled composite	NA	Increased to 8.4% for 5 wt% of filler and increases with increase in filler content	Abrasive wear increasing with the abrading distance, wear volume loss shown a linear trend. And specific wear rate decreases with an increase in load and distance.	[63,64]
18	Glass	Epoxy	TiC	VARTM	Strength increased to 11.48% for 6 wt% of filler	NA	Increased to 4% as compared to unfilled composite	The lowest specific wear rate was observed for 2 wt% of filled composite, and an increasing trend was shown with an increase in filler content beyond 2 wt%.	[65,66]

(continued on next page)

Table 1 (*continued*)

Sl. No.	Material			Manufacturing Method	Outcome				Reference
	Fiber	Matrix	Fillers		Tensile	Flexural	Hardness	Wear and Friction Coefficient	
19	Carbon	Epoxy	SiC whiskers	Hand layup	Strength increased by 14%, and modulus increased to 15.3% with 5 wt% filler	Strength increased to 8% and modulus decreased to 10% with the 5 wt% filler	NA	The coefficient of friction lowers for all filler loading. The coefficient of friction increases, and the specific wear rate decreases with an increase in sliding velocity and normal load.	[17]
10	Glass	Epoxy	PTW. and graphite	Vacuum Bagging method	Strength decreased to 5.7% with filled composite but increase in modulus to 34%	Strength decreased to 3% but the modulus increased to 20.2%	Increased to 7.3% for filled composite	PTW alone increases the coefficient of friction, but graphite predominantly reduces the friction coefficient. The wear rate was reduced to 50% for the benefit of the inclusion of whiskers and particulates.	[18]
11	Short Glass Fibers	Polyester	$CaCO_3$	Compression Moulding	Strength increased to 12.2% for 5 wt% of the filled composite compared to unfilled composite	Flexural strength and modulus increased with an increase in fiber content.	Hardness also increases with an increase in fiber content and coupling agent	The CoF is lowest for 10 wt% of the fiber, and there is no significant effect of sliding speed on CoF, and wear rate increases with an increase in sliding speed. Filled composite shows wear rate decreasing with increasing sliding distance, and is on the slightly higher side for the coarse abrasive particles.	[40,67]

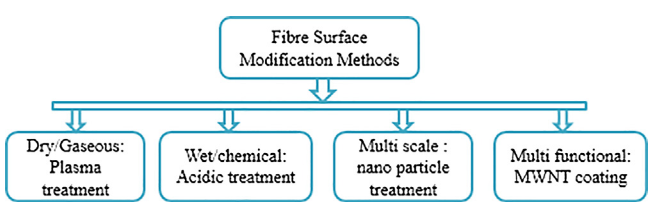

Fig. 3. Fiber and filler surface modifying methods.

due to the self-lubrication effect. Wear resistance improved due to improvement in the adhesion between fiber and matrix. Similar observations were shown by Ji et al. [76] the surface-modified SiC nanoparticles contributed to a greater decrease in friction coefficient and wear rate compared with untreated SiC nanoparticles reinforced composites. The composites with surface modified SiC nanoparticles had the greatest wear resistance even when under high contact pressure.

Two separate surface treatments such as air oxidation and cryogenic treatment were performed on short carbon fibers of epoxy matrix composites by Zhang et al. [77] Both oxidative and cryogenic treatments greatly increase the surface roughness of the carbon fiber, thus enhancing the interfacial adhesion ability of the fiber and epoxy bonding due to mechanical interlocking. Improved mechanical properties have been documented on surface-treated short carbon fibers. The cryogenic treatment has shown better improvement in modulus compared to oxidative treatment.

Besides, as proposed by many other authors, high fiber–matrix interface bonding reduce the debonding and holds the broken fibers in the matrix surface. If broken fibers are present in between it forms the third body abrasive. This study can clarify that the decreased specific wear rates observed in the surface-treated FRPs during the sliding applications.

8. Failure modes

The fracture of fiber-dominated laminates is more complicated but is typically a combination of three basic mechanisms for failure: (i) plastic deformation of the matrix, (ii) debonding of the fiber matrix, and (iii) fiber fracture. Tension failure is the easiest failure mode to be considered when analyzing the broken specimens. Several investigators have clarified the mechanisms for this mode of failure [57,78,79]. Wear phenomena are also extremely significant for understanding the wear performance in addition to the types of wear mechanisms. Mechanisms can be clearly illustrated by using the scanning electron microscope images. To understand the mechanism dependant countermeasures can follow the very simple model of Archard

$$W = k\frac{F_N}{H_w}$$

The wear rate (W) proportional to the normal load (F_N) and the hardness of the worn surface H_W and proportionality constant (k) describes the probability to generate a wear particle during the path and contains all constants and variables of a tribo-system. Surface fatigue is caused by the initiation and propagation of cracks that may happen at the surface. It depends on the contact location of the contact materials and the microstructure. Abrasion is caused by a hard or sharp substance, or protuberance forced on a (softer) surface and moving on it. Abrasion has four sub-mechanisms (micro-ploughing, micro-cutting, micro-fatigue, micro-cracking), depending on the tribo-system and the properties of the contact materials. Adhesive effects are caused by micro-joints and with subsequent degradation of every intermediate layer, body and counter-body asperities are plastically deformed. The separation takes place underneath the contact area in the non-cold operated region. There is also a transition of materials from the body to the counter body and vice versa. Tribochemical reactions are triggered by the chemical reaction of the body and counter-body materials with the interfacial medium and the atmosphere that is tribologically induced. Reaction products that are non-metallic (oxide) and thus impede adhesion are caused by tribo-chemical reactions [80,81]. A study of fundamental wear phenomena and tribological interactions is shown in Fig. 4.

Suresha et al. [57] revealed that the ductile fracture is noticeable in the GFRPs. It had to be considered because of physical interactions. There also have been brittle fractures in the composite. Plastic deformation of the matrix as shown in Fig. 5, it was concluded that the fractured nature is ductile or brittle.

The wear abraded surface photomicrograph of SiO_2 filled glass epoxy (G-E) composites measured at a load of 36 N is shown in Fig. 6 (a & b). The characteristic features of the micrographs were extreme matrix and fiber destruction at the lower abraded distance (Fig. 6b). On the surface can also be seen signs of fiber cutting, small voids left by debonded fibers. The matrix fatigue damages due to repetitive abrasion by silica sand particles, it is assumed that the fibers damaged are the result of surface fatigue. Owing to the brittle nature of glass fibers, which cracked due to repetitive abrasion by silica sand particles, the spread of crack through the fiber and interfacial debonding was also observed. The fine SiO_2 spread uniformly into G-E composites makes interfacial debonding less and thus, fibers are less exposed to abrasive medium than G-E composites, which results in less volume wear loss.

Ramakrishna et al. [83] studied the tensile properties of bidirectional knitted carbon fiber reinforced epoxy (C-E) composites. They documented the collapse of the laminates under tensile loading due to the resin matrix cracking, fiber debonding, and tensile fiber bundle fractures. It has also been found to improve its tensile characteristics by increasing the fiber content of the C-E composite. A similar kind of failure mechanism was observed for the plain weft knitted glass fiber reinforced epoxy composite [84].

M. Sudheer et al. [18] revealed the fracture behavior of glass epoxy composites filled with 7.5 wt% of ceramic filler and 2.5 wt % of graphite filler. The tensile broken surface fractures of composites are shown in Fig. 7. In the figure, the direction of tensile loading is shown with a white arrow. It was concluded that extensive splitting of fibers is due to brittle fracture. It was known that the modes of tensile failure are complicated and tensile strength is determined by longitudinal glass fibers bearing load. From a fractographic viewpoint, the most effective method is to concentrate on fiber failure. Fibers have evolved other modes of failure, such as matrix cracking and delamination.

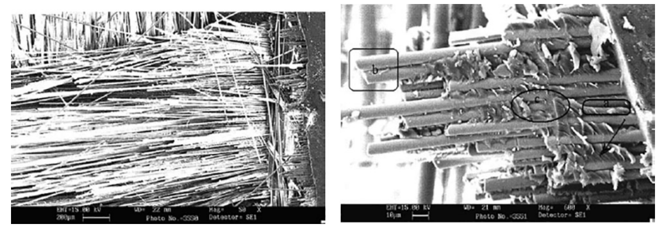

Fig. 5. (a) S.E.M. photo G-E fibre pull-out and fibre breakage. (b) S.E.M. image of G-E revealing a fibre end broken with shear deformation marks in the rich area of the matrix [57].

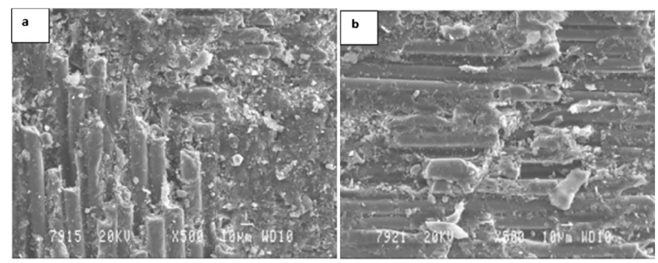

Fig. 6. SEM photomicrographs of SiO_2 filled G-E composite at 36 N load: (a) 1000 m abrading distance & (b) 250 m abrading distance [47].

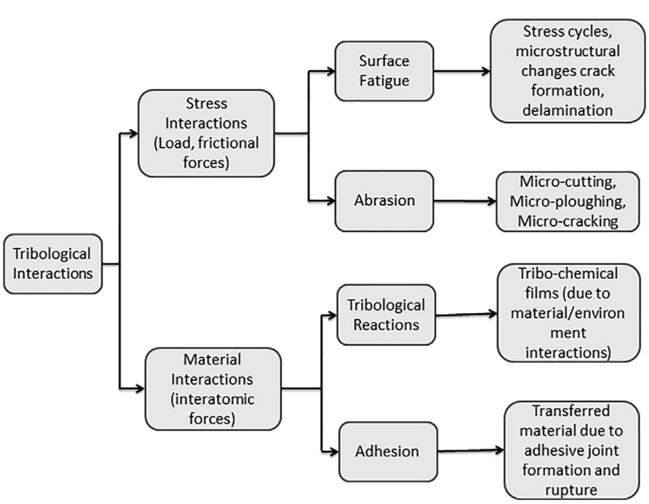

Fig. 4. Different wear mechanisms in polymer systems [82].

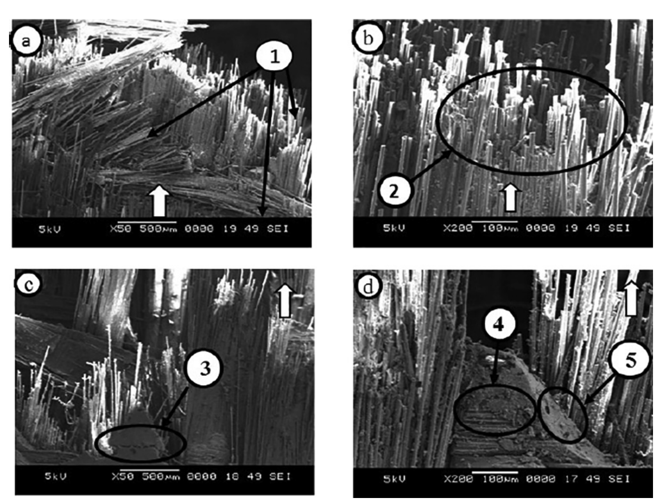

Fig.7. Tensile fracture surfaces [17].

The breakdown of the epoxy matrix is prevented by the ceramic fillers in the fiber–matrix interfacial zone, which holds the fiber in the composite and reduces the wear rate of specimens. It indicates that delamination has started between fiberglass and matrix. The glass may be debonded in subsequent sliding operation under extreme sliding conditions. The dominant mechanism of abrasive wear of polymer matrix composites caused by bulk solids is micro-cracking of the matrix caused by surface fatigue, as shown in Fig. 8. This micro-cracking often occurs as a result of ploughing in the two-body wear process. This micro cracking is the outcome of cyclic point loading when abrasive particles roll in the three-body situation. In the case of both systems, this fatigue failure on the surface can be inhibited by the use of adequate reinforcement [85].

9. Applications

Polymer composite products are independent and are widely used in the automotive, aviation, marine, and military industries. Various applications of different fiber-reinforced composites are shown in Fig. 9. In the automotive industry, the relatively high specific strength of the PMCs allows the final elements of the vehicle structures to be minimized by weight. The same pattern is observed in the aerospace field as well. There is a growing demand in the military sector for products that are distinguished by improved mechanical properties, such as the construction of military aircraft, military land vehicles (trucks & tankers), military ships, and even military equipment, such as armors and bullet-proof vests [86]. Some of the applications are listed here. The National Aerospace Laboratory CSIR-NAL (India) has built, passenger aircraft (SARAS) in which the wings and tail parts of the aircraft were developed by using carbon-epoxy composite and also other parts associated with the bottom skin such as spars, ribs, and stringers were fabricated from the advanced composites. By reduction in 1 lb of the total weight of aircraft, the company American Airlines can save 11.000 gallons of fuel per year. The various parts of the aircraft such as window frames, brackets, fittings, clips/cleats, gussets intercostals, and pans of the Boeing B-787 Dreamliner was built from composites supplied from Hexcel (USA). The automotive parts such as the chassis and external frameworks of the electric car which was developed by companies Smart and BASF (Germany), were fabricated by using carbon fibers reinforced in the epoxy matrix. The polymer wheel rim was in mass production by the company Smart Forvision. The battery pack module carrier was developed by using carbon fibers reinforced in PA6 polyamide material and is used in these three South Korean companies (LG Hansys, Hyundai Motor, and Shinhan Mold). High dense wood and steel parts were removed, and low dense glass-reinforced polymers were used in the marine industry with reducing the cost as compared to conventional materials. The company, Michael Peters Yacht Design, developed a speedboat Revolver 42, wherein the main parts of the boat deck and hull are manufactured with the help of vinyl ester resin and carbon fibers reinforced in M foam cell [87].

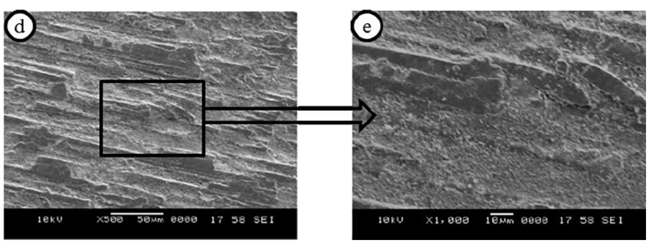

Fig. 8. Worn out surfaces of 7.5 wt% of PTW fillers and 2.5 wt% of graphite [17].

Fig. 9. Real time application of different fiber-reinforced composites.

10. Conclusion

This paper focuses on the mechanical and tribological behavior of structural components made of thermoset composites in the Aerospace, Automobile, and Marine sectors. An extensive literature has been available that documents the influence of fiber geometry, filler materials, surface modification, size of fillers, the volume fraction, and wear mechanism on the strength and stiffness of the thermoset composites.

The incorporation of fillers as secondary reinforcement in the polymer matrix seems to improve the mechanical as well as tribological properties. Also, from this review, fiber and fillers play an important role in enhancing the strength and wear resistance of polymer composites. Among all fillers, ceramic fillers can be used to improve the tensile strength, flexural strength, and hardness of composites. Internal solid lubricants like MoS_2 and graphite can enhance the wear resistance and reduce the coefficient of friction of polymer composites. An important field that is not addressed in depth in this review is the significance of nano size.

CRediT authorship contribution statement

Vijayakumar Pujar: Writing - original draft. **R.M. Devarajaiah:** Conceptualization. **B. Suresha:** Supervision. **V. Bharat:** Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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