Tribological Properties of Natural Fibre Reinforced Polymer Composites

Qumrul Ahsan, Zaleha Mustafa, and Siang Yee Chang

Abstract In this chapter, authors aim to highlight the prospect of natural fiber reinforced polymer composites (NFRPC) as tribo-materials for different engineering system. Incorporation of fibers originate from plants in polymer composite is not new as they provide environmental friendly lighter composite demanded by automative sectors where the conservation of energy is concerned. First two section gives a brief understanding on treatment of fiber surface for efficient compatibility with polymer matrix and their arrangement in composites and followed by composite fabrication for thermoset and thermoplastic composites using natural fibers. Later authors compile some published research works in order to interprete the tribo properties based on the different test parameters and composite systems impregnated by different types fibers various arrangements. Finally prospect of using hybrid polymeric composite incorporated with natural fiber and synthetic micro and Nano fillers as tribo materials is highlighted.

Keywords Tribology · Natural fibre · Polymer composites

1 Introduction

Tribology, where the two contact surfaces are in sliding with each other, mainly focuses on studying metal/metal or metal/ceramic systems for vehicles, machinery and other industrial equipment. Later, polymers light in weight and easy to fabricate are increasingly replacing the metals or ceramics in tribology. Therefore, more attention is now surfacing on the use of metal/polymer and polymer/polymer tribocontacts. Comparing the surface characteristics of polymers, it is completely different from metals and ceramics in terms of friction and wear mechanism. Polymers are susceptible to provide almost smooth and less friction motions when encounters moving counterfaces of any materials, therefore give low coefficient of friction. On the other hand, it abrades very fast when it comes into the contact of materials

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i.e. it is very weak resistant to wear. Hence, to enhance the tribo behaviour of polymeric materials by avoiding adhesion and increasing strength and stiffness (Friedrich 2018), fillers are frequently incorporated in the various polymeric systems (Aldousiri et al. 2013; Friedrich 1997; Reinicke et al. 1998) which include thermoset, thermoplastic and elastomer. Fillers are usually introduced as in the form of particles or fibers (short/long or continuous) from synthetic origin. Usually graphite and PTFE fillers act as internal lubricants in matrix which reduces the adhesion with counterpart material by forming friction reducing transfer films (Hager and Davies 1993). Whereas, artificial or synthetic fibers mainly glass and carbon fiber or special fiber aramid having high strength and stiffness are commonly added as reinforcing fillers that may retain the polymer matrix systems from tribological failure resulted from secondary crack in matrix, bended, broken and debonded fibers and generation of wear debris. One of the major concerns in tribo system is the generation of heat due to friction between two mating surfaces and because of non-conducting nature of polymer and fiber, they raise the temperature which in turn reduces the mechanical properties of composites. Therefore, polymer composites could attain resistance to thermal degradation with the introduction of carbon nano tube (CNT) and graphene particles which are termed as nano fillers with high thermal conductivity. Additionally, these nano fillers combined with other micro fillers result minimising the friction and improving the wear resistance of composite (Zhang et al. 2004).

In the recent time, environmental regulations limit the use of synthetic materials for engineering components especially in automation industries. Synthetic fillers have nondegradable constituents and adverse ecological effect for global warming. By taking advantages of the growing demand, utilisation of natural fibers lead to development of green tribo materials which are renewable and biodegradable materials (Elkhaoulani et al. 2013; Menezes et al. 2011) but have strength equivalent to synthetic fibers. These tribo materials are termed eco-friendly as the natural fibers are lighter in weight which ultimately reduce the energy consumption and pollution during use. However, natural fibers are difficult to wet by polymeric resins and compatability between fibers and resins are very low. Fibers also absorb moisture from environment due to their hydrophilic in nature. All these are affecting dimensional instability of the components with tribological failure mainly from weak interfacial adhesion between fiber and matrix (Omrani et al. 2016). However, these drawbacks are partly minimised by using chemically treated fibers and including additives. Considering the above issues, using natural fibers as an alternative to synthetic fibers could not provide better performance. Therefore, development of hybrid composites is introduced where both natural and synthetic fibers are blended in order to provide better adhesion and bonding either between fibers or between fiber and matrix (Karthikeyan et al. 2017). Eventually, the extent of performance of tribo engineering polymeric materials controls by the distribution and form of fibers or fillers as reinforcement in the polymer matrix. Components related to the properties and morphology of composites in a tribo-system are shown in Fig. 14.1.

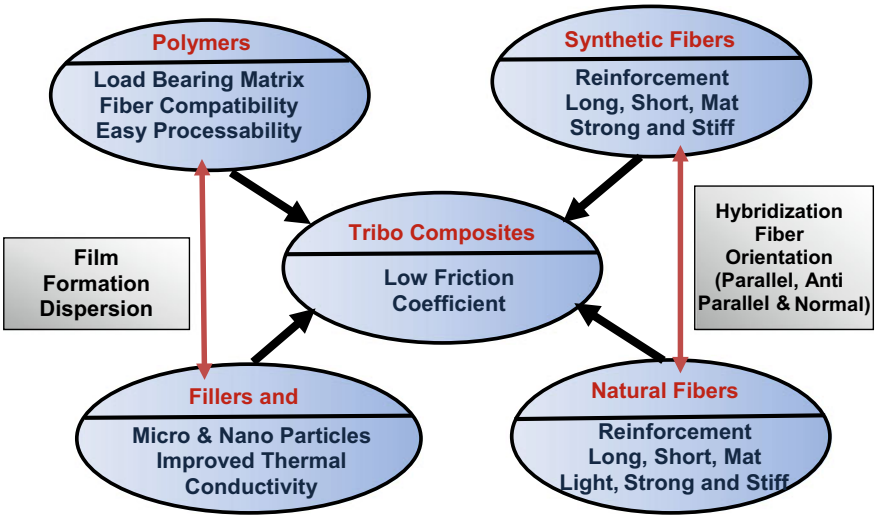


Fig. 14.1 Components for tribo composite system

2 Fiber Characteristics for Tribo Composite Preparation

2.1 Surface Modification of Fiber

Fabrication of the fibre reinforced polymer composite may pose challenges due to incompatibility between these materials. Natural fibers are polar and hydrophilic, sensitive to the moisture absorption while polymeric matrix quite often is hydrophobic, Raw natural fibres contain non-cellulosic component consist of pectin, lignin and hemicelluloses sensitive to hydroxyl and carboxylic acid groups that make them prone to water absorption (Lilholt and Lawther 2000; Zulkafli et al. 2019). Poor fibre/matrix interface bonding may hinder efficient stress transfer from matrix to the fibre which may produce inferior polymer composite with poor mechanical properties and low life span. However, surface modifications can be adopted to change the interfacial chemistry and physical nature of the fibre and reduced the incompatibility of the materials (Fadzullah and Mustafa 2016). While many approaches could be utilized to improve the surface characteristic of the natural fibers, amongst only three most widely used surface treatment process such as alkaline treatment, silane treatment and maleated coupling agent treatment will be discussed in next sections.

2.1.1 Alkaline Treatment

Chemical modification using alkaline solution is the most utilized method to improve the bonding of the natural fibres in the polymeric matrix. The method is simple,

cheap yet effective. In this method, sodium hydroxide NaOH solutions are used to modify the cellulosic molecular structure of the natural fibre (Ramli et al. 2017; Gholampour and Ozbakkaloglu 2020). The cellulose micro molecule was separated and the alkali sensitive OH groups removed from the fibre structure together with some hemicellulose, lignin, pectin and wax components (Campilho 2015; Ahsan et al. 2019). These reduce the hydrophilic nature of the fibre made it more compatible in hydrophobic polymer matrix as well as increase the moisture resistant of the fibre. Removal of the lignin and wax components from the outer surface of the fibre resulting in smoother surface conditions and smaller fibre diameter thus increase the length/diameter aspect ratio as well as the effective fibre surface area. This provides better adhesion at the fibre/matrix interface (Walker 2006). While optimum alkaline concentration should be used to ensure the effectiveness of the treatment, higher concentration of the alkaline solutions could lead to damage of the fibres. Edeerozey et al. (2007) reported that the strength of the kenaf fibre was optimum when treated in 6% NaOH concentration, however further increased of the concentration to 9% NaOH resulting in weakening of the fibre, lower than untreated fibre. Similar observation was reported by Boopathi et al. (2012) in their study of alkaline treated Borassus fruit fiber. They reported that the fibre strength was optimum when treated at 5% NaOH and further increased of the NaOH concentration (10% and beyond) significantly weaken the fibre. Brígida et al. (2010) reported that usage of the alkaline treatment on the coconut fibre not only able to retain their native hydrophilic characteristic but improve their thermal stability. In study by Nam et al. (2011) reported that the interfacial shear strength of the coir fiber reinforced poly (butylene succinate) was optimum when treated with 5% NaOH for 72 h. Morphology analysis revealed that the 5% NaOH coir fibre reinforced composite failed due to breaking of the fibre instead of interfacial failure indicating better adhesion was achieved in the alkaline treated composite in comparison to the untreated composite. Other study reported that the inclusion of the surface treatment using alkaline solutions not only able to improve the mechanical but the tribological characteristic of the composite as well (Swain and Biswas 2017; Sampath and Kumar 2019). Valášek et al. (2018) studied the influence of the alkali solutions onto the mechanical and abrasive wear of the coir reinforced epoxy composites and reported that alkaline treatment effectively improved the tensile strength as well as wear resistance of the composite.

2.1.2 Silane Treatment

In this method, the fibre is immersed in the silane solution for a period of time allowing the coupling agent in the solutions to coat the micro pore on the surface of the natural fibre. Silanol then formed using the hydrolyzable alkoxy group that present. The bonding between natural fibre and matrix forms via a link known as soloxage bridge. One end of the forms sialon chain attached to surface of the natural fibre surface by creating a formation with their cellulose OH group and the other end links with functional group in the matrix thru a condensation process (Faruk et al.

2012). Subsequently, molecular continuity is created across the fibre/matrix interface (Campilho 2015; Gholampour and Ozbakkaloglu 2020). Reports have shown that mechanical properties of the composite using silane treatment could be significantly improved, often better than alkaline treatment. This is due to alkaline treatment removed impurity on the natural fibre and provided bonding via mechanical interlocking while silane provides chemical links attachment from the coupling agents. Yallew et al. (2014) reported that while all treated jute fibre showed improved wear resistance when imbedded in polylactide matrix composite, silane treated jute exhibited highest wear resistance resulting from the strong interfacial adhesion produced by coupling linkage. Mayandi et al. (2018) reported that the mechanical strength of natural fibre exhibits better mechanical properties and thermal stability when subjected to silane treatment in comparison to alkaline treatment. Liu et al. (2019) investigate the impact of silane treatment on mechanical, tribological properties of the corn stalk fiber (CSF) reinforced bio-polymer composites while selecting four different silane concentration (1, 5, 9 and 13 wt%). This work revealed that while silane-treated CSF could not effectively improve the friction performance, however it is able to significantly increase the wear rate of the polymer composites.

2.1.3 Maleated Coupling Agent Treatment

In this approach, maleic anhydrite (MA) is grafted with the polymer which is used as a matrix material; then it is allowed to react at the interface of the natural fibre and matrix. MA reacts with hydroxyl group that is located in the amorphous region of the cellulose structure to form a covalent bond while the aliphatic chain of MA gets diffused and links with polymer chains of matrix via carbon-carbon bonds (Fuqua and Ulven 2008; Anbupalani et al. 2020). The MA chemically attached to the surface of the fibre serves as a bridge between the fibre and matrix in order to improve the interfacial adhesion. Hong et al. (2008) attempted to modify the surface of jute fibres by maleic anhydride treatment and to improve the interaction between jute fibre and matrix phase and to enhance the mechanical properties of the jute fibres reinforced polypropylene. Morphology analysis revealed that treated jute fibre were broken without complete pull-out in comparison to the untreated composite. This indicated improved fibre-matrix adhesion at the interface as the result of the MA modification. Kakou et al. (2014) investigated the dispersion of the oil palm fibre in the high density polyethylene (HDPE) matrix in the presence of maleated coupling agent. They reported that the treatment has effectively boost the stiffness due to better adhesion between the fibres and matrix. Catto et al. (2014) evaluated the effect of various MA concentration on the tensile strength and stiffness of the maleated polyethylene grafted recycled HDPE and eucalyptus fibre. They reported that addition of 3% of MA in composite shows the highest mechanical properties indicated better compatibility and improved interfacial adhesion achieved in the presence of MA.

2.2 Size and Texture of Fiber Pattern (Short, Long and Mat)

The fibre can be arranged in the matrix in various designs such as continues or discontinues, woven arrange in form unidirectional or bidirectional, random as well randomly distributes (Fig. 14.2). The fibers are very significant part of a fibre-reinforced composite material, since the fibre characteristic such as length, orientation and their loading significantly alter the mechanical properties of the composite (Jusoh et al. 2015; Fadzullah et al. 2016) and may as well its ultimate tribological behaviour.

In order to study the influence of the fibre orientation onto the wear properties of the composite, the sliding direction could be applied in three conditions as shown in Fig. 14.3 such as:

- Parallel (P-O): fibre mat and fibre orientation are in the parallel direction to the sliding direction
- Normal Orientation (N-O): fibre mat and fiber are in normal orientation to the applied force and parallel to the sliding direction
- Anti-Parallel (AP-O): fibre mat and fiber are in the perpendicular direction to the sliding direction.

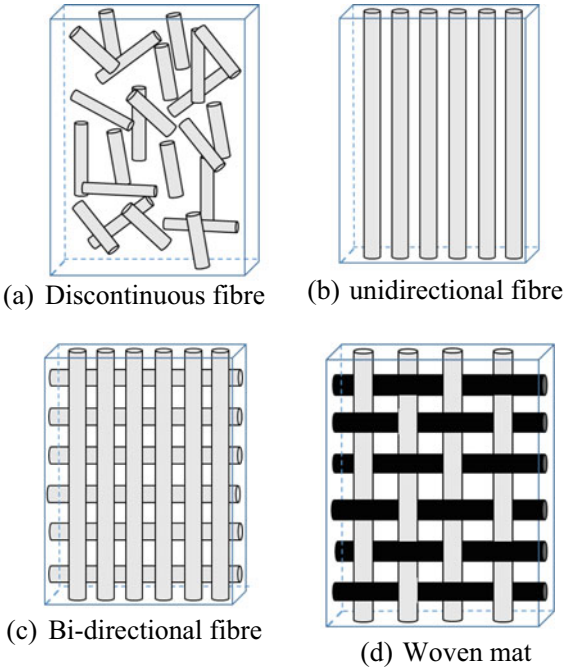


Fig. 14.2 Various types of fibre reinforcement pattern

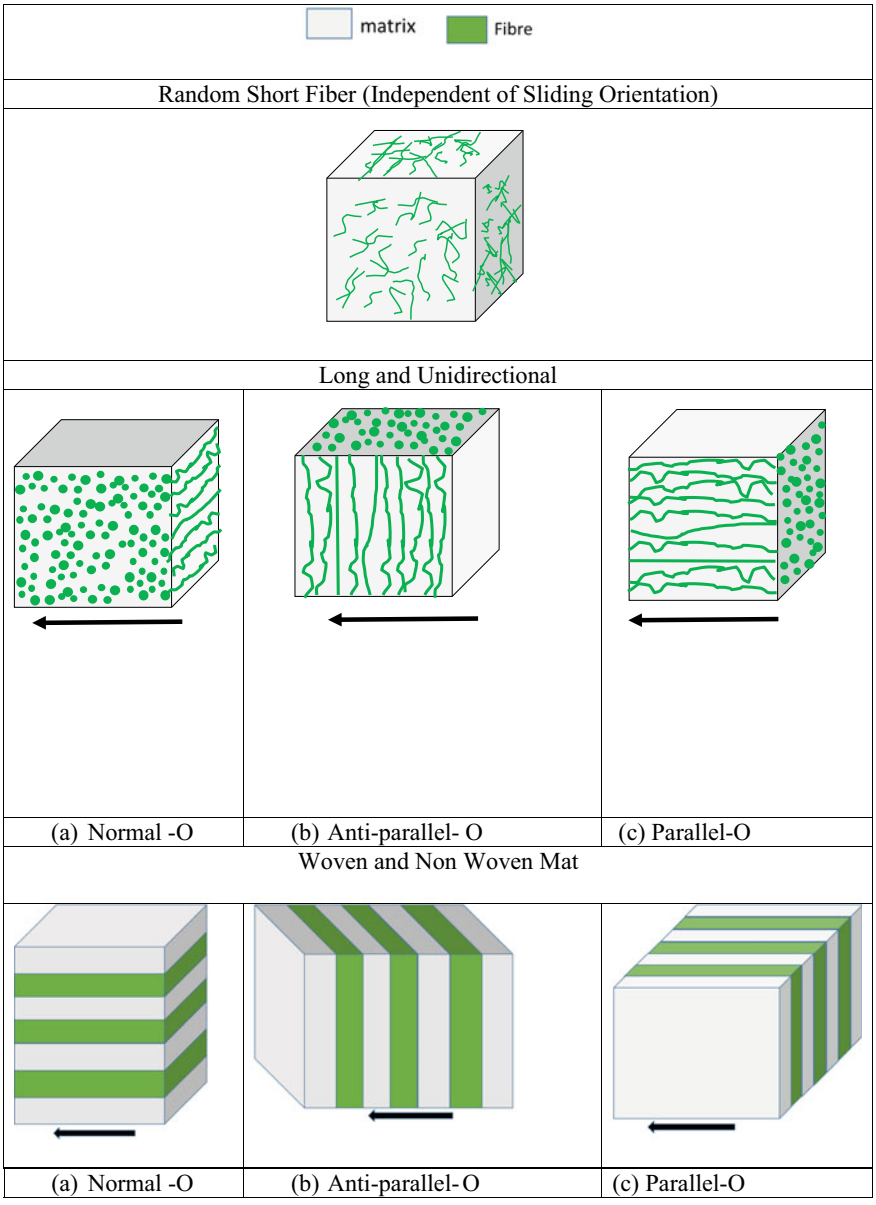


Fig. 14.3 Schematic illustration of composite orientations and sliding direction

3 Processing of NFRPC (Tribo Composite)

3.1 Natural Fibers in Thermoset Composites

Processing of natural fibers reinforced thermoset polymers mainly depends on the size type and texture of natural fibers as well type of thermoset. Usually fibers are in the form of short, long or mat. Thermosets also known as resins are in the liquid form where the short fibers are impregnetaed randomly or resin-saturated long continous fiber are placed layer by layer in unidirectional, bidirectional woven mat form and allow for curing either at ambient temperature or at elevated temperature with or without pressure. The fiber impregnated resin is completely solidified to composite through polymerisation of resins. Hand lay-up, spray lay-up, hot compression molding are low cost and popular techniques used to fabricate unsaturated polyester and epoxy composites. On the other hand complicated and expensive techniques such as resin transfer moulding (RTM), pultrusion, vacuum bagging are being used for higher quality epoxy or phenolformaldehyde composite products.

3.2 Natural Fibers in Thermoplastic Composites

In case of thermoplastic composites, dispersion and distribution of short fibers in plastic matrix or the wetting of long continous fiber by thermoplastic are the critical issues in composite fabrication as the plastic resins are in the solid form. Short fibers are mixed with plastic resins in cyclone vortex or internal mixer where both fibers and thermoplastic are premixed and converted to pellet shape. Later these pellets are used in injection or hot compression molding. Whilst for long or mat fibers hot compression molding or thermoforming processes with different time and temperature interval stages are utilisied for proper wetting of the fibers by thermoplastic. Usually the fabrication cost for natural fiber thermoplastic composites are usually high as they are produced by expensive equipment such as extrusion, injection molding or hot compression molding machine but as the natural fibers are less abrasive the maintance cost of the equipment are low in composite production. Usually, engineering thermoplastics are required high temperature in the range of 200–350 °C which is not suitable for natural fibers as most of them degrade at or above 180 °C. This processing factor, therefore, limits the use of engineering thermoplastics whereas PE, PP and PU which have low processing temperature are being used with lignocellulosic fibers. Some typical natural fiber compatiable thermoset and thermo plastic products using different processing techniques are shown in Table 14.1 (Karthikeyan et al. 2017).

Table 14.1 Processing methods of various natural fiber reinforced thermoset and thermoplatic composites in tribilogical applications (Karthikeyan et al. 2017)

Fiber	Matrix	Test conducted	Processing method
Banana and Kenaf	Polyester	Mechanical wear test	Hand lay-up
Rice straw dust/rise husk dust	Phenolic	Friction assessment and screening test	Hot pressing
Sugarcane/glass	Polyester	Adhesive friction and wear	Hand lay-up
Linen/jute	Polyester	Dry friction wear test	Casting process
Sisal	Phenolic	Constant speed tester	Hot compression
Betelnut	Polyester	Mechanical pull-out wear and friction	Hand lay-up
Sea shell nano powder	Poly-methyl methacrylate	Wear micro-hardness	Mold
Jute	PP		Injection molding machine
Kenaf	PU		Hot compression mold

4 Tribological Characterization of NFRPC

Natural fiber reinforced thermoset and thermoplastic composite materials are now attempting to fabricate as tribo materials specially to perform in dry and non-lubricated condition. This is due to the composite's low density contributed from using light weight natural fiber and in some cases, these composites have better specific stiffness and strength provided tribological properties comparable to many tribo materials that are currently used. Tribology of natural fiber reinforced polymer composites (NFRPC) usually provide information on tribo properties and wear mechanisms in composite system. First term is closely related to material removal and energy dissipation at the surface through transfer layer formation, contact temperature, and degradation of composites whereas the last term mainly focuses on damages of fibers and polymer matrix, debonding of fibers characteristics of wear debris.

4.1 Testing and Evaluation of NFRPC

All of the above features are characterised by considering the typical test parameters that are relative movement of test piece and counter surface, surface nature of counter face, sliding speed, sliding distance, applied load, test temperature and environment etc. used in tribo testing. So far research test data for NFRPC obtained from dry sliding wear test using pin on disk (POD), block on disk (BOD) or block on ring (BOR) test systems in order to determine the coefficient of friction μ, wear loss, w_L and the specific wear rate w_s by the following equations:

$$\mu = F_R/F_N \tag{1}$$

where F_R is the friction force and F_N is the normal load measured in N.

$$w_L = Dm = w_i - w_f, \text{ in g} \tag{2}$$

where w_i is the initial weight and w_f is the final weight taken before and after the test respectively

and

$$w_s = \Delta m/(\rho F_N L) = \Delta V/F_N L; \text{ expressed in } mm^3/Nm \tag{3}$$

where Δm is the weight loss, ρ is the density of the composite material, ΔV is the volume loss, and L is the sliding distance.

The specific wear rate can be termed as "material property" or "wear factor (k^*)" of the material (Friedrich 2018) in tribology and could be comparable between tribo materials as long as test conducted under equivalent condition. From test data, researchers also calculated the wear rate depth $w_{t.}$ (reduction of specimen per unit time) and plotted against the *pave* product (normal pressure times sliding velocity) and found that there exists a nearly straight line relationship with a slope of w_s or k^* ($= w_t/pv$) provided w_s is independent and not influenced by changes in either contact pressure (p) or sliding velocity in the test system and the relationship is plotted schematically in Fig. 14.4 (Friedrich 2018). Figure 14.4 clearly shows that w_s remains constant up to certain pv product beyond that w_s is no longer constant

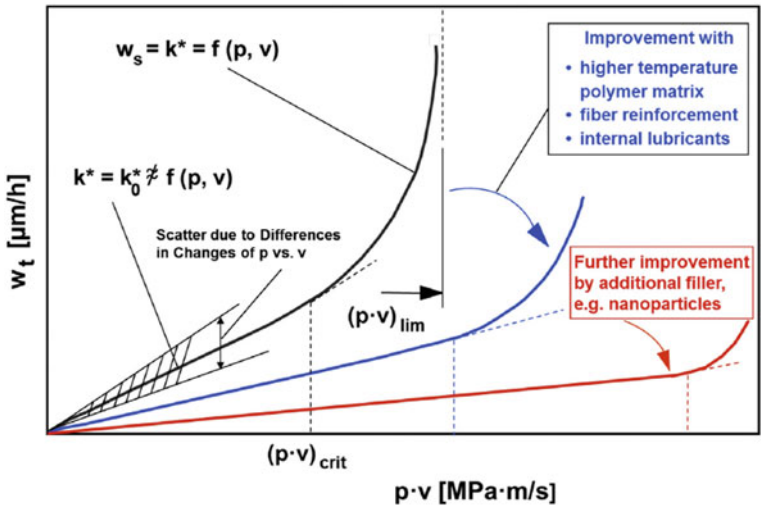


Fig. 14.4 Test parameters for the enhancement of wear behaviour of polymer composites (Friedrich 2018)

and indicates the unstable behaviour of the material. Therefore, *pv* limit is used to indicate the onset of catastrophic failure of composites due to thermal softening and fracture. It is also evident from Fig. 14.4 that using different reinforcements and fillers in given polymer reduce the slope (lowering w_s) and push the limiting *pv* values towards higher values (Friedrich et al. 2018). Therefore, it is expected that incorporation of natural fibers in polymer matrix would manifest lower slope in w_t vs *pv* plot construction as compared to that in matrix alone. The tribological properties such as friction and wear of natural fiber reinforced polymer composites (NFRPC) are controlled by the adhesion between the polymer matrix and metallic counterpart and worn out of natural fiber respectively in performance system.

4.2 Friction in NFRPC

It is associated with the release of energy due to chemical-mechanical damages take place at the mating surfaces as adhesion and/or for the loss of material due to ploughing (Briscoe and Friedrich 1993). The term friction force and its value are generally used to monitor the adhesion of surfaces of polymer composites and metallic counterpart. The initial rise of the friction force in tribo system is due to unstable adhesion film formation (unsteady state) on the contaminated surfaces. With further progress of sliding, deformed asperities cause increase of surface areas which increases adhesion and stabilise the friction force shortly after starting the test. Previously theory of friction was adhesion based where friction force associated with friction originated from contact area of surface asperities. But experimental values of friction coefficient in most cases do not tally with theory. Hence bulk properties such as ploughing is also considered in addition to adhesion to narrow down the discrepancy between the experimental values and theoretical values of friction coefficient.

Evidence of lower friction force or friction coefficient for the presence of natural fiber either in nondegradable or biodegrables polymers were reported by researchers (Yallew et al. 2014; Bajpai et al. 2013). The friction force and coefficient of friction in pure polypropylene matrix and polymer matrix wth jute fiber mat at three different sliding speeds and applied loads were studied for a total sliding distance of 3000 m (Yallew et al. 2014). In both cases steady state friction force values reached within a very short period of travel and it is indepedent of applied load but the friction force increases as the applied load increases and at any applied load (Fig. 14.5). The friction force and coefficient of friction of pure PP is always higher than that of PP-Jute Fiber composite. In case of pure polypropylene, plastic debris once sticks to the sliding interface, instead of getting thicker it deforms by consuming energy and thus increases the friction force as it can be seen in SEM of polypropylene surface. On the other hand, in NFRPC, usually steel surface is very hard and rough which usually ploughs the softer polymer surface, removes the polymeric materials and causes wear of sliding surface. That is why ridges are observed along the sides of ploughed grooves under the scanning electron microscope.

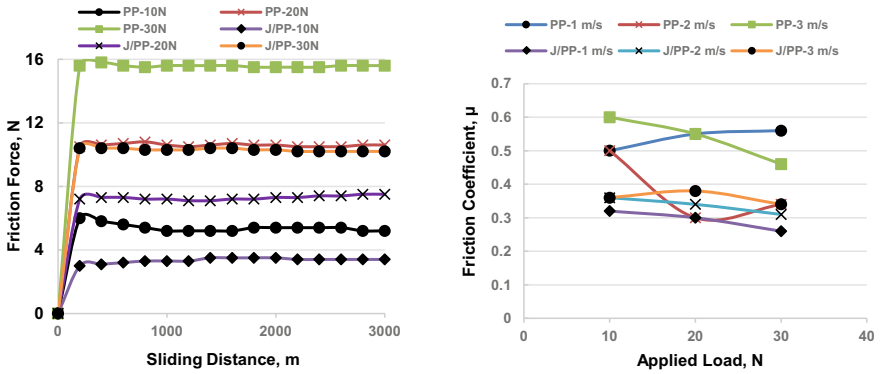
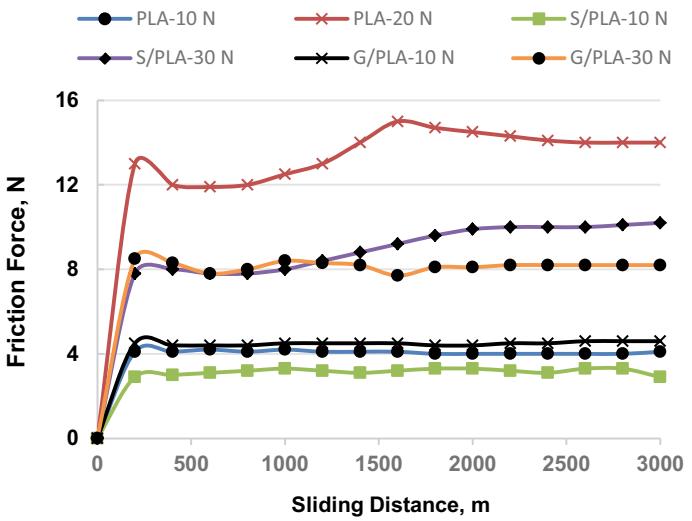


Fig. 14.5 Variation of **a** friction force against the sliding distance for PP and Jute/PP at sliding speed of 3 m/s and **b** friction coefficient against applied load for PP and Jute/PP (Yallew et al. 2014)

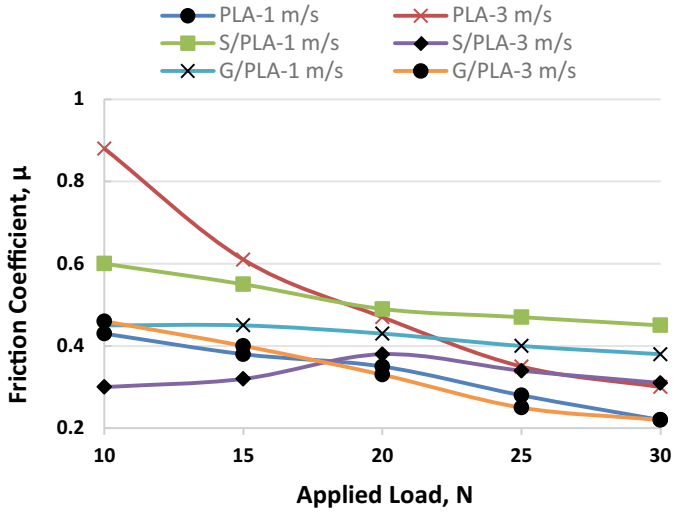
Similar effects were also observed by Bajpai et al. (2013) when they studied tribo behaviour poly lactic acid (PLA), PLA-glass and PLA-sisal composites (Fig. 14.6). Interestingly, sisal fiber in composites has observed a lower value of friction force and COF as compared to pure PLA and PLA-Glass composite at any contact load. CoF is not an intrinsic property of materials, it also depends on the test type, temperature, type of film formed and nature of fiber used. Unlike metals, polymer softens with the rise of temperature and for this, fiber easily debonded from the polymer matix and mix with polymer debris which alter the charecteristics of polymer adhesion later. Obviously natural fiber like sisal stiffens the polymer layer but not like as glass polymer layer. Hence polymer protective layer with the presence of natural fibers deforms platically more which reduces the friction co efficient (El-Tayeb 2008a, b; Yousif and EI-Tayeb 2008).

4.3 Wear in NFRPC

In tribo system, wear is defined as the loss of materials of two bodies when their contact surfaces are moving relative to each other [Chand and Fahim (2008)]. Although wear does not cause sudden failure of material, but certainly reduces the performance characteristics from changing and deforming the shape of the components or from surface damage. Hence volume changes in materials causes vibration and surface damages formed secondary cracks that may lead to collapse of the components. Although the common forms of wears are adhesive (sliding), abrasive, corrosive, erosive and fretting but first two forms prevail mainly in NFRPC. Schematic illustration of the major form of dry sliding wear mechanisms are summarized in Fig. 14.7.



(a)



(b)

Fig. 14.6 Variation of **a** friction force against the sliding distance for PLA GF/PLA and Sisal/PLA at sliding speed of 2.8 m/s and **b** friction coefficient against applied load for PLA, GF/PLA and Sisal/PLA (Bajpai et al. 2013)

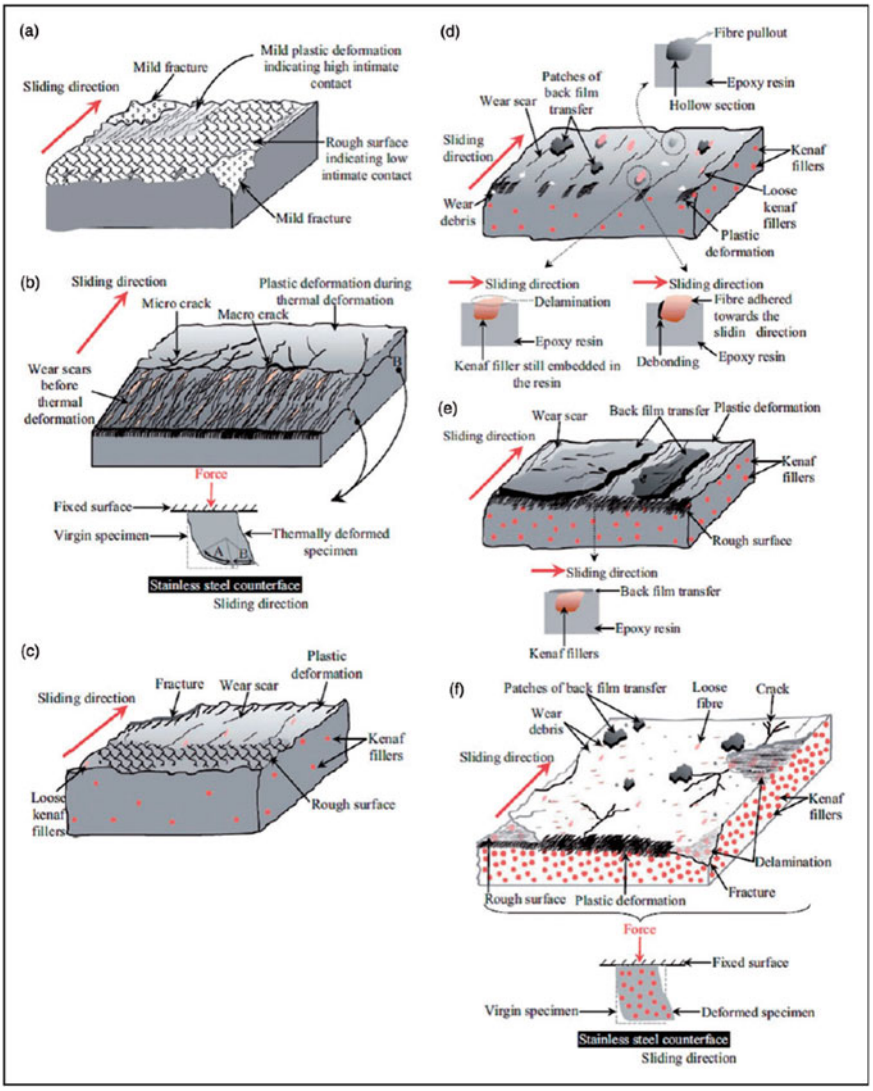


Fig. 14.7 Schematic illustration of different dry sliding wear mechanisms (Rajini et al. 2012)

The tribo properties such friction and wear are dependent on the total test system and not sole related to material properties and vary by changing the test parameters. Although no direct relationship could be made between tribo properties and mechanical properties (strength, stiffness, hardness etc.) of materials, but mechanical properties are utilised to explore the correlation between wear resistance and friction coefficient. It is widely established that synthetic reinforcements (fibers and fillers) are stronger and more wear resistant than polymer matrix therefore, the presence of

fiber not only utilise to transfer load from matrix to fiber and increase the strength of the composites but also minimise the exposition of the polymer for counterface. The wear performance of fiber reinforced polymer composites depend not only on the size, shape, volume and orientation and type of fiber but also the extent of adhesion between fiber and matrix. Proper wetting of fibers by polymers is one of the biggest issue in processing of composites and beyond the optimum loading, usually fibers starves from matrix wetting resulted in low mechanical and tribo properties as the fibers can readily debonded from the matrix, Generally, long fibers usually impregnated in the form of bi- or uni-directional mat in polymer matrix improve the wear resistance of composites very significantly, whereas short fibers are easily wetted by polymer which may improve the friction and rapid mouldability. Usually natural fibers are hydrophilic (attracted by water) and polymers are hydrophobic (repels water) which may cause poor interfacial bond between fiber and matrix and may lead to poor wear performance of the composite. In addition, natural fibers easily absorb water which may cause swelling of the composites with debonding of fibers. It can also easily be attacked by the microorganism and become weak which may reduce the composite service life.

Therefore, chemical treatments on natural fibers are usually carried out to increase the hydrophobicity and to improve the interface bonding between fibers and polymers. One of the prime consideration in polymer and its composites is load-temperature interaction. Hence, temperature at wear surface is usually measured during wear test in order to monitor the thermal softening of polymer that can lead to increase in the real areas of contact resulted in rapid increase of both the coefficient of friction and the wear.

In case of natural fibre reinforced composites, various kinds of fibers (jute, sisal, coir, oil palm, flax, hemp, bamboo) are reinforced in thermosets and thermoplastics either as chopped short or continuous fibers. The chopped short fibers are randomly distributed in polymer matrix as reinforcement, whereas continuous fibers not as long as synthetic fibers are placed in matrix as uni- or bi-directional woven fabric or mat. The direction of sliding force to orientation (parallel, anti parallel and normal) of natural fibers also control the properties of composites. Table 14.2 summarizes the tribo test results obtained from published research work for various polymer composites impregnated with different types natural fibers. The table also provides information on the fiber treatments and their corresponding consequence on friction and wear rates that are plotted in Fig. 14.8.

It is apparent from Fig. 14.8 that pristine thermoplastic polymers with low specific wear rates manifest significant improvement in wear resistance when impregnated with reinforcing natural fibers. Jute has been reported as high strength and high modulus (Chand and Fahim 2008), therefore jute fiber reinforced polypropylene exhibits the lowest wear rate a lower w_s of the order of 10^{-7} m^3/Nm and a low friction coefficient of 0.3 while coir reinforced polyester composites exhibit a high w_s of the order of 10^{-4} m^3/Nm and a high friction coefficient of 0.6. Improvement on wear resistance and friction for jute composite compared to coir composite is attributed to higher stiffness and strength with better selflubricating (lesser abrasive) ability of jute fibers. Once again jute or oil palm fibers reinforced epoxy also exhibit

Table 14.2 Tribological data for the natural fiber reinforced thermoset and thermoplastic composites

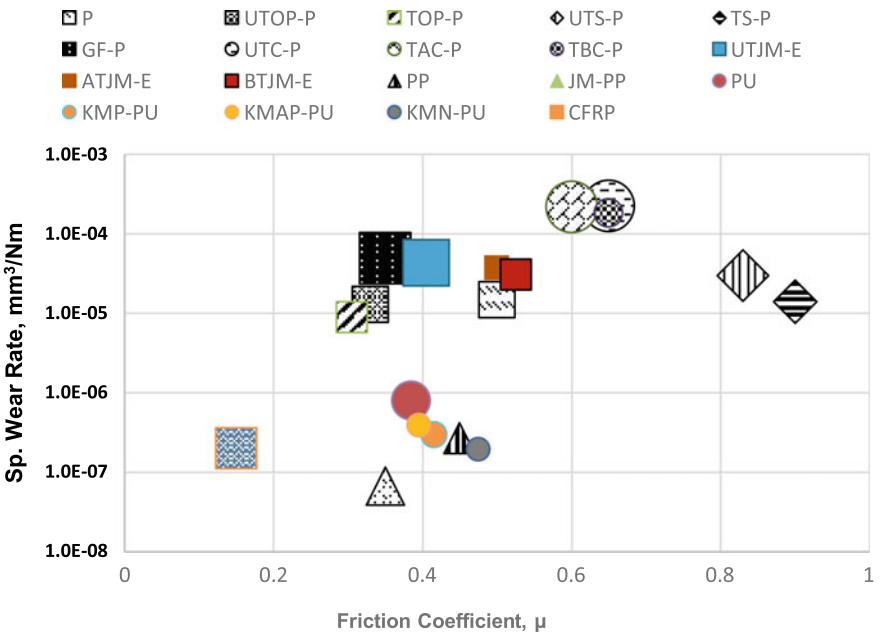
Matrix	Fiber	Fiber vol.%	Type of testing	Counter face	Test parameters			Tribological properties			References
					Applied load, N	Sliding speed, m/s	Sliding distance, km	CoF, μ	Wear rate, $mm^3/Nm \times 10^{-5}$	Interface temp., °C	
Polyester		0	POD	Stainless Steel	30–100	2.8	0–5 km	0.4–0.6	0.4–2.6	25–54	Yousif and EI-Tayeb (2008)
	UT-oil palm short random	48						0.46–0.2	1.0–1.6	25–45	
	T-oil palm short random							0.21–0.4	0.4–1.4	25–45	
Polyester		0	POD	Steel EN 32	10–100	1.75	0–6	0.5	1.0–2.0	40–60	Chand and Dwivedi (2007)
	UT-Sisal short random	27						0.83	3.6–2.4	55–100	
	T-Sisal short random							0.9	1.8–1.0	70–100	
Polyester		0	BOD	Stainless Steel	20	2.8	0–5	0.62–0.96	12.0–15.0	25–45	Yousif (2008)
	Oil palm short mat	25						0.5–0.85	18.0–12.0	22–25	
	Glass long mat	25						0.2–0.5	4.0–6.0	23–34	
Polyester	UT-coir long unidirectional	25	POD	Stainless Steel	10–30	2.8	4.2	0.5–0.65	37.0–8.0	40–70	Yousif et al. (2009)
	AT-coir-long unidirectional							0.4–0.6	18.0–76.0	30–60	
	B-coir long unidirectional							0.3–0.65	30.0–7.0	30–60	

(continued)

Table 14.2 (continued)

Matrix	Fiber	Fiber vol.%	Type of testing	Counter face	Test parameters			Tribological properties			References
					Applied load, N	Sliding speed, m/s	Sliding distance, km	CoF, μ	Wear rate, $mm^3/Nm \times 10^{-5}$	Interface temp., °C	
Epoxy	UT-jute woven mat	10–40	TBAW	Dry Sand (100–400 μm/Rubber Wheel	10–40	Not Reported	50–80 m	0.26–0.55	3.0–5.75	NR	Swain and Biswas (2017)
	AT-jute woven mat							0.4–0.6	3.0–4.5	NR	
	BT-jute woven mat							0.3–0.75	2.4–3.75	NR	
Polypropylene		0	POD	Steel EN 32	10–30	3.0	0–3	0.3–0.6	0.022–0.32	NR	Yallew et al. (2014)
	Jute mat	40						0.3–0.4	0.0035–0.0098	NR	
Polyurethane		0	BOD	Stainless Steel	30–60	2.8	0–2.7	0.2–0.57	0.01–0.15	NR	
	P-Kenaf Mat (bi directional)	38						0.21–0.62	0.005–0.055	40–130	Narish et al. (2011)
	AP-Kenaf Mat (bi directional)							0.27–0.52	0.003–0.075	50–140	
	N-Kenaf Mat (bi directional)							0.32–0.63	0.005–0.034	40–120	

UT—untreated, AT—alkali treated, B—bleached, BT—benzoyl treated, P—parallel, AP—antiparallel, N—neutral, POD—pin on disc, BOD—block on disc, TBAW—three body abrasive wear, NR—not reported



P-Polyester, UT-Untreated, OP- Oil Palm, T-Treated, S-Sisal, C-Coir, AT-Alkaline Treated BT-Benzoyle Treated, E-Epoxy, K-Kenaf, GF-Glass Fiber, J-Jute, CF-Carbon Fiber, PP-Polypropylene, PU-Polyurethane, M-Mat, P-Parallel, AP-Antiparallel, and N-Normal.

Fig. 14.8 Friction coefficient and specific wear rate of various natural fiber reinforced polymer composites in sliding wear mode. (Data are collected from research works included in Table 14.2)

equivalent tribo properties compared to glass fiber reinforcement in different wear modes. This may attribute to the fact that the high fiber contents in thermoset resins act as load bearing agents that control tribological properties by fiber reinforcement.

Figure 14.9 shows the specific wear rate results of glass fiber, untreated and alkaline treated oil palm and coir fibers under similar tested conditions (Yousif and EI-Tayeb 2008; Yousif et al. 2009) and their test details are provided in Table 14.2. Specific wear rate of the composites predominantly varies by the sliding distance except for glass fiber composites which shows steady wear rate and almost independent of sliding distance. Results also manifest that for unidirectional coir epoxy composite, longer the sliding distance, higher the specific wear rate whereas specific wear rate of the randomly distributed oil palm fibers in epoxy composites increases with increase in sliding distance. On comparison, for alkali treated both fibers reveal better wear resistance than the composites with untreated fibers. Result from fiber treatment with NaOH resulted in removal of gummy contents (pectin, lignin etc.), which may rise the roughness of fiber surface and develop better mechanical locking with high-interfacial adhesion between fibers and matrix. The SEM studies of worn surfaces for two treatment conditions are different where the surface cracking, fiber

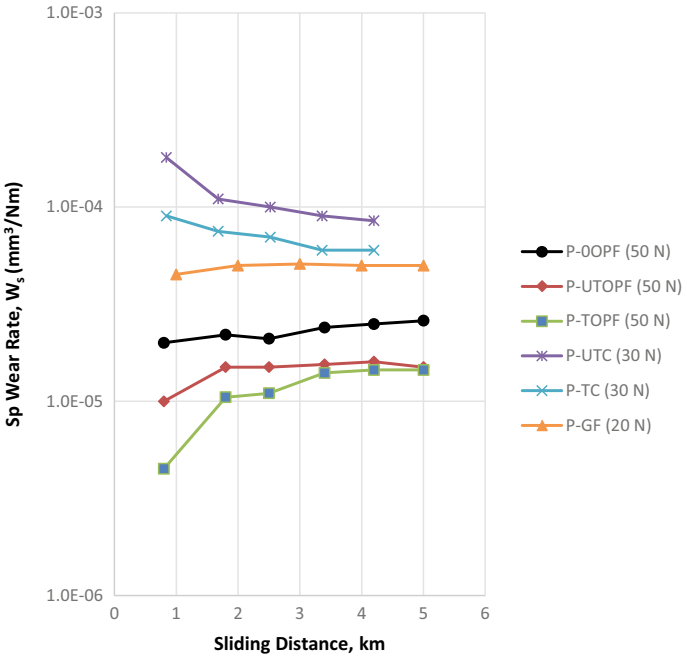


Fig. 14.9 Effect of chemical treatment on specific wear rate of different sliding distances for oil palm and coir fiber reinforced polyester composites at a sliding speed of 2.8 m/s in similar test condition. (Plots are reconstructed from research works of Yousif et al. 2009; Yousif and EI-Tayeb 2008; Yousif 2008)

debonding with abrasion (ploughing) are predominant in untreated fiber reinforced composite compared to that in treated fiber reinforced composites.

4.4 Fiber Orientation on Wear

The role of fibers as reinforcements in composites affect the composite wear especially when the sliding force direction of sliding plane encounters the fibers at different orientations i.e. parallel, anti-parallel and normal respect to the sliding plane. Usually short fibers imbedded in composite are in all directions therefore wear in composite is independent of sliding direction but for long continuous fiber depending on its orientations the effect of wear is substantial as the combination of different wear mechanisms are controlled by the fiber orientation. The effect of the type of fiber orientations on specific wear rate and friction coefficient under different test conditions are summarized in Table 14.3 and Fig. 14.10.

Among all the composites in Fig. 14.10, carbon fiber reinforced in a thermoset resin exhibits the lowest wear rate and friction coefficient in sliding wear mode

Table 14.3 Tribological data for the natural fiber reinforced thermoset and thermoplastic composites

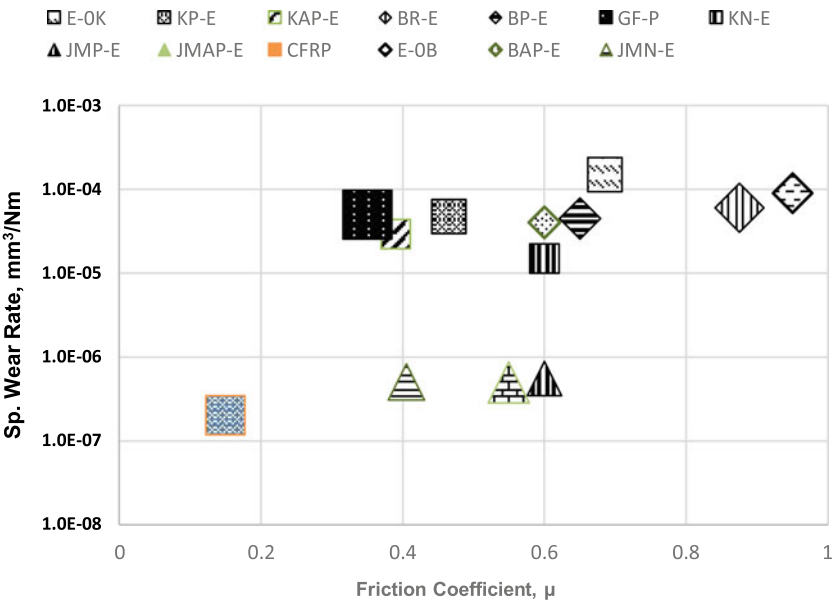
Matrix	Fiber	Fiber vol.%	Type of testing	Counter face	Test Parameters			Tribo Properties			References
					Applied load, N	Sliding speed, m/s	Sliding distance, km	CoF, μ	Wear rate, $mm^3/Nm \times 10^{-5}$	Interface Temp., °C	
Epoxy		0	BOD	Stainless Steel	30–100	2.8	0–5	0.65–0.72	14.0–16.0	42–68	Chin and Yousif (2009)
	Kenaf (unidirectional) P	48						0.35–0.58	6.0–3.5	41–61	
	Kenaf (unidirectional) AP							0.36–0.42	3.8–2.0	35–49	
	Kenaf (unidirectional) N							0.52–0.68	1.0–2.0	43–65	
Epoxy		0	POD	Stainless steel	30	1.7–3.96	0–4	0.9–1.0	11.0–7.0	30–95	Nirmal et al. (2012)
	Bamboo (random)	45						0.85–0.9	5.0–7.0	30–92	
	Bamboo (unidirectional) P							0.55–0.75	3.5–5.5	30–78	
	Bamboo (unidirectional) AP							0.5–0.7	3.0–5.0	30–75	
Epoxy		0	BOD	Sic particles	1–7	2.56	6–25.6 m	NR	26.0–11.0	NR	Chand and Dwivedi (2008)
	Sisal (unidirectional) P	50							18.0–10.0	NR	

(continued)

Table 14.3 (continued)

Matrix	Fiber	Fiber vol.%	Type of testing	Counter face	Test Parameters			Tribo Properties			References
					Applied load, N	Sliding speed, m/s	Sliding distance, km	CoF, μ	Wear rate, $mm^3/Nm \times 10^{-5}$	Interface Temp., °C	
	Sisal (unidirectional) AP								13.0–8.0	NR	
	Sisal (unidirectional) N								12.0–7.0	NR	
Epoxy	Jute short fiber mat P	35	BOR	Stainless Steel	30	3	10	0.6	0.007–0.004	NR	Alshammaria (2018)
	Jute short fiber mat AP							0.6–0.9	0.0068–0.003	NR	
	Jute short fiber mat N							0.26–0.55	0.003–0.007	NR	

P—parallel, AP—antiparallel, N—neutral, POD—pin on disc, BOD—block on disc, BOR—block on ring, NR—not reported



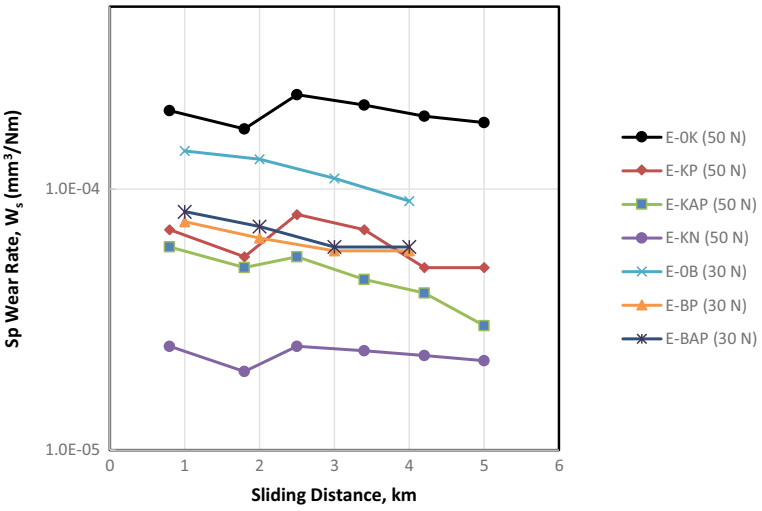
E-Epoxy, K-Kenaf, B-Bamboo, GF-Glass Fiber, J-Jute, CF-Carbon Fiber, R-Random, M-Mat, P-Parallel, AP-Antiparallel, and N-Normal.

Fig. 14.10 Effect of fiber orientation on friction coefficient and specific wear rate of various natural fiber reinforced polymer composites in sliding wear mode (Data are collected from research works included in Table 14.3)

where bamboo fiber reinforced composites have the highest wear rate and friction coefficient. Although, for any group of composites fiber orientations have substantial contribution on wear rate, friction coefficient of composite exhibit low to high value in the order of N < AP < P orientation. El-Tayeb (2008a, b) conducted a series of studies on the tribological properties of natural fibre. In order to evaluate the effect of the fibre length onto their wear properties, sugarcane fibre with length ranging from 1, 5 and 10 mm were arranged in random orientation (R–O) and subjected to 20–80 N of applied normal loads, at constant sliding velocity of 2.5 m/s, and constant sliding distance of 2.25 km. The main finding indicated that wear rate were decrease with increase of fibre length. In his second study (2008), he focused on influence of the fibre orientation by using two conditions where the sliding forced direction was applied in anti-parallel orientation (AP–O) and parallel orientation (P–O) with respect to the mat orientation. He reported that P–O shown a significantly higher weight loss than AP–O. Morphological analysis revealed that no obvious fracture in the AP-O due to high interfacial adhesion of the fibres and matrix as compared to the P-O direction. This is because that in P-O orientated fibre, there was a higher chance for the failure due to fibre pull-out as the sliding force is applied in parallel to the fibre orientation. Narish et al. (2011) studied the wear properties of treated kenaf

fibres reinforced polyurethane (PU) composites at different applied loads (30–60 N), at constant sliding velocity of 2.8 m/s at different fibre orientations of anti-parallel orientation (AP-O), parallel orientation (P-O) and normal orientation (N-O). They reported that wear performance compared to neat PU, giving an improvement in specific wear rate (Ws) at 78% in comparison to neat composite. In regards to PU, adhesion film forms during wear and manifests low friction due to smoother sliding resulted from thermal softening of PU. Considering the case for composites, fibers debond from matrix but it adheres with the soft PU film and makes the film stiffer that may improve the wear performance but with high friction. Alshammaria et al. (2018) aims to correlate the influence of fibre orientation on tribological performance of the alkaline treated jute mat in the epoxy matrix. They were using three different orientations with respect to sliding force such as N-O, AP-O and P-O. The main finding of their work revealed that fibre orientation has very significant contribution to the wear and friction properties of the composite. The optimum condition of the wear resistance was obtained when the composite was tested in antiparallel condition.

Figure 14.11 shows the effect of fiber orientation on specific wear rate of kenaf and bamboo fiber composites at different sliding distances in similar test conditions (Chin and Yousif 2009; Nirmal et al. 2012). Obviously presence of kenaf or bamboo fibers in composite shows the improved wear performances as compared to that of neat epoxy under same tribo conditions and the specific wear rate of the composites decrease when sliding distance increases. For normally oriented (N) kenaf fibers wear rate is lower when compared with P or AP conditions. This is attributed to more film



E-Epoxy, K-Kenaf, B-Bamboo, P-Parallel, AP-Antiparallel and N-Normal

Fig. 14.11 Effect of fiber orientation on specific wear rate for different sliding distances of kenaf and bamboo fiber reinforced epoxy composites at a sliding speed of 2.8 m/s in similar test conditions (Plots are reconstructed from research works of Chin and Yousif 2009 and Nirmal et al. 2012)

formation by normal (N) oriented fibers as compare to normal AP/P conditions where debonded fiber volumes are higher and worn out of the matrix rapidly instead of forming film. Usually in normal orientation fibers are perpendicular to worn surface so the contact area is only the diameter of each fiber whereas in parallel or anti parallel orientations fibers in length wise are exposed. Therefore, for a given volume fraction of fiber, the effective fiber contact area is less for N orientation as compare to A or AP orientation.

Chin and Yousif (2009) proposed the wear mechanism for the three tested orientations shown in Fig. 14.12 in terms of damages of fibers that are different for P, AP and N orientations. In case of P orientation (cf. Figure 14.12a), long length of fibers encounter sliding force which could bend and break the fibers along the sliding direction if the sliding force exceeds the interfacial adhesion strength. Even at certain condition when the sliding force is lower than the adhesion strength, splitting of fibers may occur and finally fibers could tear and break. For AP orientation, in addition to debonding and bending, detachment of fibers may occur when the sliding force is higher the interfacial adhesion as shown in Fig. 14.12b. On the other hand, there is less possibility of fiber debonding when the fibers are in N orientation (Fig. 14.12c) where the fibers diameters are only exposed and the fibers are embedded inside the

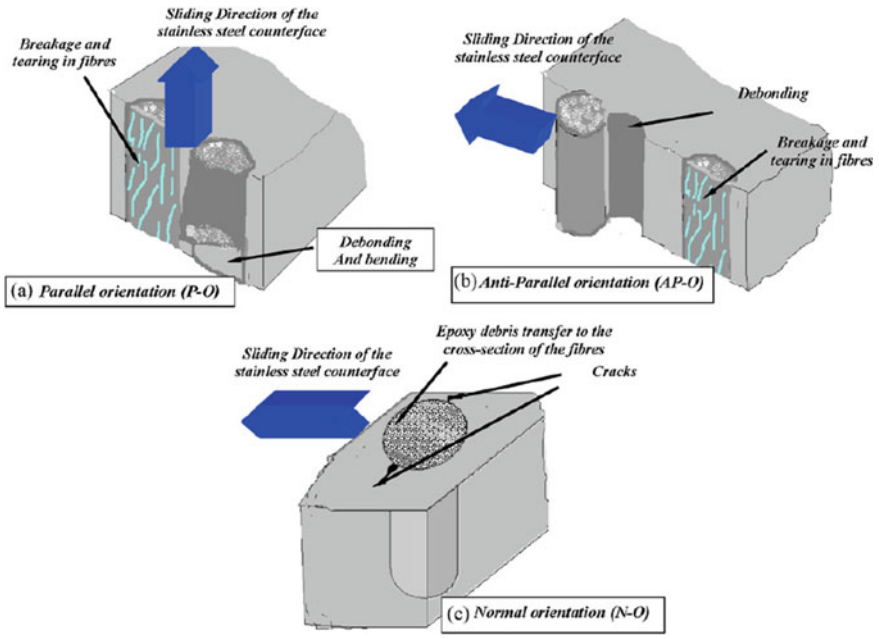


Fig. 14.12 Proposed wear mechanism of the composites in **a** parallel, P, **b** anti-parallel, AP and **c** normal, N orientations (Chin and Yousif 2009)

Table 14.4 Polyethylene-based composites (Satov 2008)

Function	Material	Dosage range (%)
Matrix component	Polyethylene resin	Difference from total of other components of 100%
Reinforce component	Natural fiber	30–60
Coupling agent	Maleated polyolefin	2–5
Lubricant(s)	Stearates/esters/EBS/other	3–8
Antioxidants	Phenolics/phosphites	0–1
Acid scavengers	Stearates/hydrotalcites	0–1
UV protection	HALS/benzophenones/benzotriazoles	0–1
Mineral filler	Talc	0–10
Biocide	Zinc borate	0–2
Density reduction	Microspheres\chemical or physical blowing agent	0–5
UV protection/aesthetics	Pigments	As required
Flame retardants/smoke suppressants	Various	As required

matrix along their length. But the sliding force may generate secondary crack perpendicular to matrix around the fibers due to shearing force. Worn surface morphology characterised by SEM further clarified the proposed mechanism.

4.5 Role of Additives in NFRPC

Additives are part of the important recipe in fabricating tribo-composites owning to its role in manufacturing process and end product performance. Generally, additives are used based upon typical formulas and industrial norms, and are modified whenever necessary. Satov (2008) revealed that composite industries tend to use additives to make up for process deficiencies due to the lack of coordination between end product requirements and materials-process technology, resulting in an increase of operational cost in a long run. It is, hence necessary to optimize the usage of additives through proper integration of materials, process technology and product performance. Tables 14.4 and 14.5 summarize the functions, materials and dosages for polyethylene- and polypropylene-based composites.

4.5.1 Solid Lubricants

In order to develop a good tribo-composite component, incorporating the composites with specific fillers and/or additives is essential to achieve special requirements

Table 14.5 Polypropylene-based composites (Satov 2008)

Function	Material	Dosage range (%)
Matrix component	Polyethylene resin	Difference from total of other components of 100%
Reinforce component	Natural fiber	30–60
Lubricant(s)	Stearates/esters/EBS/other	3–8
Antioxidants	Phenolics/phosphites	0–1
Acid scavengers	Stearates/hydrotalcites	0–1
UV protection	HALS/benzophenones/benzotriazoles	0–1
Mineral filler	Talc	0–10
Biocide	Zinc borate	0–2
Density reduction	Microspheres\chemical or physical blowing agent	0–5
UV protection/aesthetics	Pigments	As required
Flame retardants/smoke suppressants	Various	As required

for tribological applications, such as exhibiting low friction characteristics while maintaining good mechanical strength. Solid lubricants such as graphite, molybdenum disulfide (MoS_2), poly-tetrafluoroethylene (PTFE) (Chang and Friedrich 2010; Konovalova and Suchanek 2012; Panda et al. 2016; Shalwan and Yousif 2013, 2014; Sharma et al. 2017; Subramanian et al. 2016), hexa-boron nitride (hBN), tungsten disulphide (WS_2) (Panda et al. 2016) and boric acid (H_3BO_3) (Mutlu et al. 2007; Reeves et al. 2013) have been widely employed in polymer composites to enhance wear performance by reducing wear rate and friction coefficient of the composites.

These solid lubricants are generally useful in developing a uniform transfer layer on the surface of hard metallic counterpart, which hamper the direct contact between the two sliding bodies and thus protect the composites from severe abrasive wear (Chang and Friedrich 2010; Shalwan and Yousif 2013). The molecular structure of these solid lubricants which is composed of layers of atoms bonded together by weak van der Waals force rendered the formation of transfer film upon dry sliding (Reeves et al. 2013). Figure 14.13 illustrates schematic representations of the layered crystal structure of graphite, MoS_2, hBN and H_3BO_3 molecules. Addition of these solid lubricants in the composites leads to the development and usage of a new class of materials called self-lubricating polymer matrix composites, which are highly sought after in mechanical and tribological components such as gears, cams, wheels and impellers. These self-lubricating composites fulfilled the increasing industrial demand to operate in machineries subjected to relative movement where no external and/or fluid lubricant shall be used (Suresha et al. 2010).

In general, the presence of solid lubricants demonstrated significant reduction of coefficient of friction and wear rate in various polymer matrix composites (Bijwe and Indumathi 2004; Hashmi et al. 2007; Shalwan and Yousif 2014; Zhang et al.

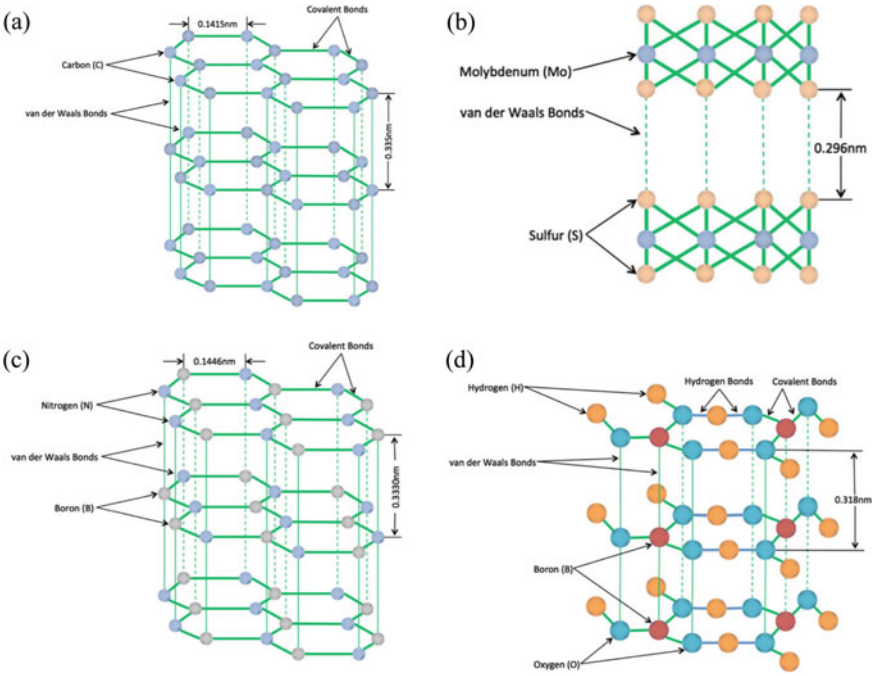


Fig. 14.13 Illustration of layered crystal structure of **a** graphite C, **b** molybdenum disulfide MoS_2, **c** hexa-boron nitride hBN and **d** boric acid H_3BO_3 molecules (Reeves et al. 2013)

2008). Several researchers reported on the reduction of coefficient of friction and wear rate as a function of solid lubricant concentration (Hashmi et al. 2007; Suresha et al. 2010; Zhang et al. 2008). Coefficient of friction as low as 0.1 was reported in poly-(phthalazinone ether sulfone ketone) (PPESK) composites filled with 30 wt% graphite (Zhang et al. 2008) under 500 N sliding load. Nevertheless, it is also noted that the presence of high solid lubricant content results in the deterioration of mechanical properties of the respective composites (Shalwan and Yousif 2014; Zhang et al. 2008). However, Suresha et al. (2010) inferred that treating the graphite filler with silane coupling agent led to improved interfacial adhesion and proper dispersion of graphite filler in carbon-epoxy composite, and subsequently enhanced the tensile strength, Young's modulus and hardness of the composite.

Whilst these solid lubricants exhibited desirable frictional characteristics, thermal conductivity of these solid lubricants must also be considered as frictional heat generated could harshly affect the friction and wear mechanisms. Solid lubricants having high thermal conductivity are preferable in tribo-composites applications, allowing heat dissipation from the tribo-surface and hence minimizing damage to the component surface. Hashmi et al. (2007) reported that contact interface temperature reduced with increasing amount of graphite filler in their work on graphite/cotton fibre reinforced polyester composites under sliding wear condition. Similar trend was also

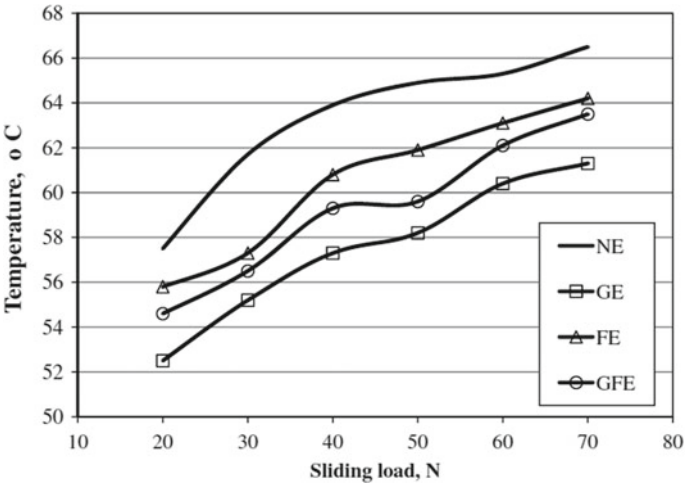


Fig. 14.14 Interface temperature of different epoxy composites based on graphite and/or date palm fibre at different applied loads after 5.04 sliding distance using block-on-ring (BOR) technique. *NE: neat epoxy; GE: 3% graphite/epoxy; FE: Date palm fibre/epoxy; GFE: 3 wt% graphite/date palm fibre/epoxy* (Shalwan and Yousif 2014)

observed by Shalwan and Yousif (2014) wherein the lower interface temperatures were recorded in wear test when 3% graphite was added into both neat epoxy and date palm fibre reinforced epoxy composites, as illustrated in Fig. 14.14.

However, among all the solid lubricants, graphite and hexa-boron nitride (Panda et al. 2016) are the promising candidates and their related properties are detailed in Table 14.6. In fact, Bijwe and Indumathi (2004) found that the PTFE is not the right choice for high temperature lubrication in tribo-composites, unless PTFE is used in a combination with graphite and MoS_2. More recently, Panda et al. (2017) highlighted that synergistic effect of two solid lubricants (15% graphite and 5% hBN) incorporated in the glass fibre reinforced polyaryletherketone (PAEK) exhibits the lowest friction coefficient (0.04) and specific wear rate (5.68×10^{-16} m^3/Nm) compared to

Table 14.6 Characteristic properties of high performance solid lubricants (Panda et al. 2016)

Material	h-BN	Graphite	PTFE
Density (g/cm^3)	~2.1	~2.1	2.15
Bulk modulus (GPa)	36.5	34	1.8
Thermo-oxidative stability (°C)	1000	570	260
Thermal conductivity (W/m K)	600[a]; 30[b]	200–2000[a]; 2–800[b]	0.25
Thermal expansion (10^{-6}/°C)	−2.7[a]; 38[b]	−1.5[a]; 25[b]	−148
Specific heat capacity (J/kg K)	710–830	840–1610	1000

Effect of fiber orientation on tribo properties
[a]Parallel to planes/layers; [b]Perpendicular to planes

that of single solid lubricant. It is expected that such remarkable synergism at 15% graphite and 5% hBN was due to improved thermal conductivity and fibre-matrix adhesion (Panda et al. 2017).

4.5.2 Nanoparticles

In line with the advancement in nanomaterials, incorporation of various nano-sized inorganic particles such as ZrO_2, Al_2O_3, SiO_2, SiC, TiO_2 and CuO in polymer matrices has attracted great attention due to significant enhancement in tribological performance (L. Guo et al. 2017). Konovalova and Suchanek (2012) emphasized that significant size reduction of these particles down to nano-scale level leads to a completely distinct wear behaviour and better properties under dry sliding conditions with advantages of:

i. Generally lower abrasiveness due to reduced angularity;
ii. Enhanced strength, modulus and toughness due to defect-free structure;
iii. Higher specific surface areas and thus, improved filler-matrix adhesion; and
iv. High effectiveness at very low contents.

Several researchers (Cho and Bahadur 2005; Guo et al. 2009; Shao et al. 2004) pointed out that the enhanced bonding between the nanoparticles and polymer matrix due to the high surface area-to-volume ratio of the nanoparticles, led to strengthening of the transfer film. The transfer film formed during the dry sliding wear was fairly thinner and smoother, hence providing a better coverage on the steel counterpart surface, resulting in lower friction coefficient and wear rate of the composite materials. Furthermore, it was highlighted that the smaller the particles, the better was the wear resistance of the composites; and the optimum filler content of these nanoparticles ranges between 1 and 4 vol.% to avoid the tendency of particle agglomeration (Zhang and Friedrich 2005).

On the other note, Chang and Friedrich (2010) investigated the effect of TiO_2 nanoparticles on the dry sliding wear of short carbon fibre reinforced polymer composites with addition of conventional tribo-fillers, i.e. graphite and PTFE. It was found that addition of 5 vol.% of nano-TiO_2 could significantly reduce the friction coefficients and contact temperature, especially under high pv (the product of p (pressure) and v (velocity)) conditions. The results clearly indicated that the presence of nano-TiO_2 which acts as 'spacers' at the contact region effectively reduce the adhesion between the transfer film and polymeric specimen, rendering a lower coefficient of friction. Figure 14.15 compares the wear mechanisms for sliding wear of short fiber reinforced polymer (SFRP) composites between with and without inclusion of nanoparticles.

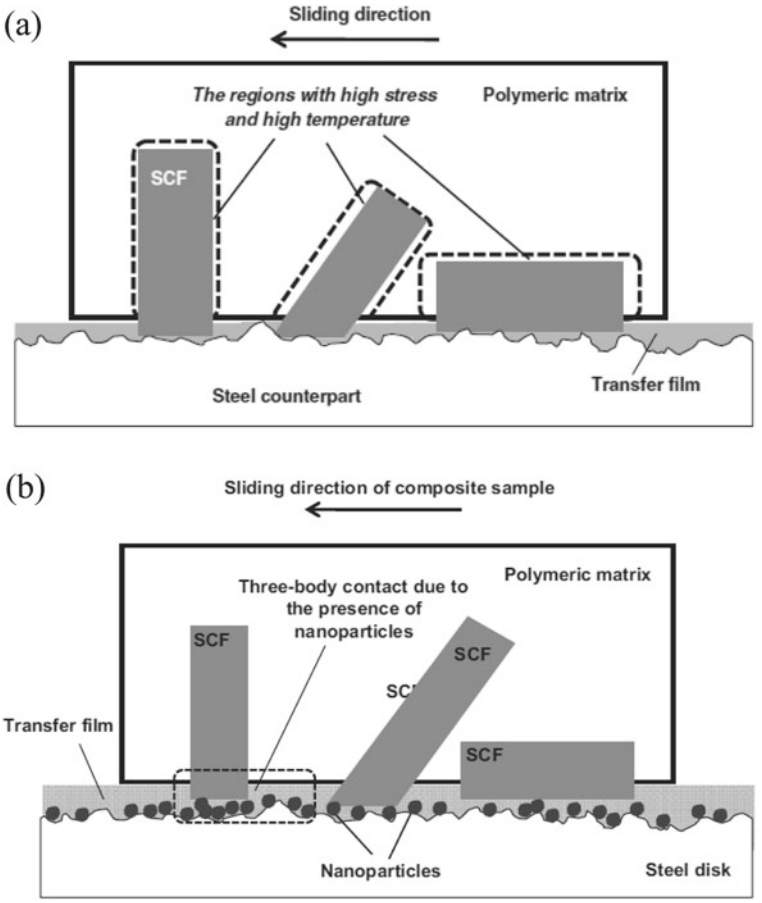


Fig. 14.15 Schematic illustration of the failure mechanism for the sliding wear of SFRP composites **a** with and **b** without nanoparticles (Chang and Friedrich 2010)

5 NFRPC as Tribo Materials

NFRPCs have emerged as a potential alternative to synthetic fiber reinforced composite as they minimize harmful pollutants and reduce the environmental impact. In some occasions natural fibers are expected to perform close to that of synthetic fibers especially brake pads for automotive. With great care fabrication must ensure the homogeneous distribution of fibers with a high thermal resistance to withstand severe temperature during braking. Several research teams are developing automotive components dedicated to tribo system by replacing a substantial amount of synthetic fibers by natural fibers (ECOPAD). Various natural fibers reinforced polymer hybrid composites with limited tribological applications have been illustrated in Table 14.7.

Table 14.7 Various natural fiber reinforced hybrid composites in tribological applications (Karthikeyan et al. 2017)

Fiber	Matrix	Fiber treatment	Tribological application
Banana and Kenaf	Polyester	NaOH, sodium lauryl sulphate	Clutch
Rice straw dust/rise husk dust	Phenolic	Untreated	Brake pad
Sugarcane/glass	Polyester	Untreated	Bearing
Linen/jute	Polyester	Untreated	Bearing
Sisal	Phenolic	Silane coupling	Brake pad
Sea shell nano powder	Poly-methyl methacrylate	Untreated	Dental

6 Conclusion and Future Perspective

The concept of completely replacing synthetic fillers by natural fiber does not provide solutions for using materials as engineering components while considering its properties and dimensional stabilities. Although natural fibers polymer composites are lighter as compare to synthetic composites but degrades drastically when come to contacts during service even though the natural fibers are modified chemically. Incorporating synthetic fillers in NFRPC not only enhance load-carrying capacity, but also considering for the improvement of wettability and compatibility between the fiber and the matrix. The role of hybridisation by blending natural and synthetic fillers in polymer composites has not been elaborated substantially in tribo testing of composites. Therefore, the design of hybrid composites using natural fibers and synthetic fillers mainly focuses on the reduction of water or moisture absorption with adequate adhesion between fiber and matrix for the development of improved wear and friction properties. Cotton fiber and graphite filler in modified polymers were designed initially to develop hybrid composite with significant reduction in the specific wear rate as well as reduction in contact temperature at the interface due to presence of conductive graphite filler. Subsequently, nanomaterials such as carbon nanotube and graphene are found to be efficient nanofillers for polymer composites due to their good mechanical strength with high thermal conductivity which resist the thermal gradation of composites. These synthetic nanofillers not only transport the heat efficiently but also reduce the abrasion as they have high aspect ratio with reduced angularity edges. Hence the wear performance of nano filler composites may be significantly improved better from that of micro-particle filled systems.

Introduction of nano fibrillated cellulose (NFC) synthesised from any plant fibres rich in cellulose (e.g. oil palm empty fruit bunches, bamboo pulps, jute fibers, kenaf and others) as nano fillers in tribo composite materials could be the key challenge for future research projects. NFC may display thermo-mechanical properties comparable to available synthetic and non-biodegradable graphene/CNT nano fillers and

ensure to fabricate tribo-composites which till date has not been reported in research. Eventually, the overall research activities will emphasize the benefits of fabricating natural and environmentally friendly tribo materials in order to convert renewable resources to high value end products which possess lesser or no harm to environment.

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