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Tribological properties of polymeric composites: A review

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Abstract

Tribology deals with interacting surfaces in sliding, rolling or any others types of motions, which is much importance in designing for machine components to improve their durability's of mechanical engineering systems. This study overviews the most recent studies on the tribological behavior of polymeric based materials containing different fillers. Some microstructural and mechanical properties of the epoxy composite are introduced. In addition, mechanisms of increasing wear resistance and reducing friction coefficient for polymeric composites are reviewed. An overview is also covered the process optimization for the dry wear results of polymeric composites using Taguchi Method (TM) and Response Surface Method (RSM). Furhermore, future use of the fiber reinforced composites in tribological applications is included in this study.

1. Introduction

Because of combinations of higher strength/higher modulus, lower density and lower cost associated with chemical resistance and easy for processing, fiber reinforced polymeric composite materials are finding increased applications in many industrial applications such as airspace/airplane, automotive, marine, construction and packing industries for many years.

Composite materials are normally consisted of at least two or more phases. One phase is a matrix, which is the continuous phase, but weaker one while other one is particulates or fibers generating the dispersed phase, which have higher stiffness and strength. In generally, polymeric matrices can be epoxy, polyester, vinyl ester, polytetrafluoroethylene (PTFE), polyphenylene Sulfide (PPS) and polyamide. Off course, these polymers are used for the making various polymer matrix composites (PMCs) to obtain better mechanical and physical properties. The reinforcements can be formed as fibers, fabrics, whiskers or particulates [1]. The best mechanical properties can be obtained using unidirectional fibers while balance properties can be provided with the fabric types. As for the case of particulate-reinforced composites, their form abilities are easy to produce and lower cost when compared to the others [2]. For manufacturing PMCs; glass, carbon, basalt and boron fibers or fabrics are selected for unidirectional orientated or bidirectional composites while silicon carbide (SiC), aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), and graphite (Gr) are widely used for the particulate reinforced composites. Carbon fiber is best selection for such applications when compared to short fiber, particulate and whiskers because of providing larger ordering properties. Continuous fiber reinforced composites are designed and manufactured in many structural applications to obtain more strengths and rigidities for airspace, ship and chemical industries. But the particulate reinforced composites exhibited improving abrasion wear property, especially for friction and wear applications such as cylinder blocks, pistons, piston insert rings, brake disks and calipers in addition to lower cost [3]. In addition, epoxy based polymeric composites are preferred structural components such as helicopter rotor blades, horizontal/vertical stabilizers, airframes in aerospace industry while leaf springs, heavy duty bearings, bus and car with hydrogen combustion engine in automotive industry while rollers/bearings and filament wound composite bushings reinforcing with continuous fiber reinforcements are used in mechanical engineering applications. When the fabric forms of the carbon are used, the best properties are provided in terms of mechanical, tribological point of view and load carrying capacity. There are numbers of important factors such as fiber orientation, fiber length, type of matrix and fiber, fiber diameters, processing applications and interface bonding affect the mechanical properties for polymer/metal composites [4,5].

The composite materials are undergone to the tribological behavior at abrasive sliding for numbers of applications. Wear may be categorized as adhesive, abrasion, surface fatigue and tribo-chemical, fretting, erosion and cavitations wear. Abrasive wear takes place as hard asperities on one surface move across a softer surface, penetrate and remove material from the softer surface [6,7]. The abrasive wear problems in mostly occur for chute liners in power plants, mining and earth moving equipment. Material's losses are inevitable because of the relative motion of these sliding parts of any machine, but if it is over a critical limit, catastrophic failure of machine elements take

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place and results in big economic losses. Therefore, wear rate's prediction is critically importance to determine the life of sliding components in advance due to wear.

Design of experiment (DOE) is a systematic method for the collection and analysis of data. Recently, many scientific people are adopted the statistical techniques such as Taguchi method (TM) and Response Surface Methodology (RSM) to develop a mathematical relation and to find out a better combination between input and output parameters for different processes and products. The Taguchi uses a special design of orthogonal array to optimize the quality characteristics. The effect of variations or variables on the quality characteristics focused for this method [8]. Also, Response Surface Methodology (RSM) use an empirical modeling approach to find out the relations between input parameters and their responses. Second order RSM model gives more accurate results. This design methodology is more appropriate for optimizing the nonlinear behavior of systems or large groups.

This study overviews the most recent studies on the tribological property of polymeric matrix containing different fillers. Some mechanical and microstructural properties are also introduced besides failure mechanisms in describing the lower wear and coefficient of friction. In addition, an overview is concentrated on the process optimization by Taguchi and RSM for the dry/abrasive wear testing results of epoxy reinforced composites.

1.1 Why is tribology?

Tribology concentrates on friction, wear and lubrication for all contacting pairs of materials. To improve machine component's life and reliabilities, their safeties, tribological knowledge is required. Wear is the progressive losses of materials owing to relative motion between the surface and the contacting substances [9]. Failure of the component takes place due to adhesive wear. Adhesive wear causes uneven surface that resulted in a reduction in mechanical contacting area. For the same subjecting load, the reduction in mechanical contacts increases the stress' levels and thus, components failure occurs significantly.

The failure rate of any tribo-pair, two machine components in relative to sliding motion, depends upon the surface roughness of machine components. To minimize the surface roughness a soft coating on the surface is preferred due to its easy elastic deformation. In other words, wear on the rough surfaces usually occurs quickly and a higher friction coefficient is obtained than smoother surface. What is the economic benefit? Implementation of tribological knowledge provides economic benefits because it reduces energy loss due to friction and loss due to breakdowns. A number of examples can be shown for reducing the friction and wear properties such as I.C. engines, turbo machinery, gears, cam-followers, bearings and seals.

1.2 Tribological system and its function

Friction and wear issues are not material properties, but they are responses to a specific tribological system and many factors affect the systems. The tribological sub-system is shown in Figure 1 that providing the common factors affecting the friction and wear values [10]. This tribological system is consisted of the operational inputs such as load, type of motion, sliding speed, temperature, etc., its structure like tribo-elements, interfacial/ambient medium and the functional behavior like power, material, motion, etc., and loss outputs. The system-structure is determined by the properties of the substantial elements containing the base and opposing body with various medium.

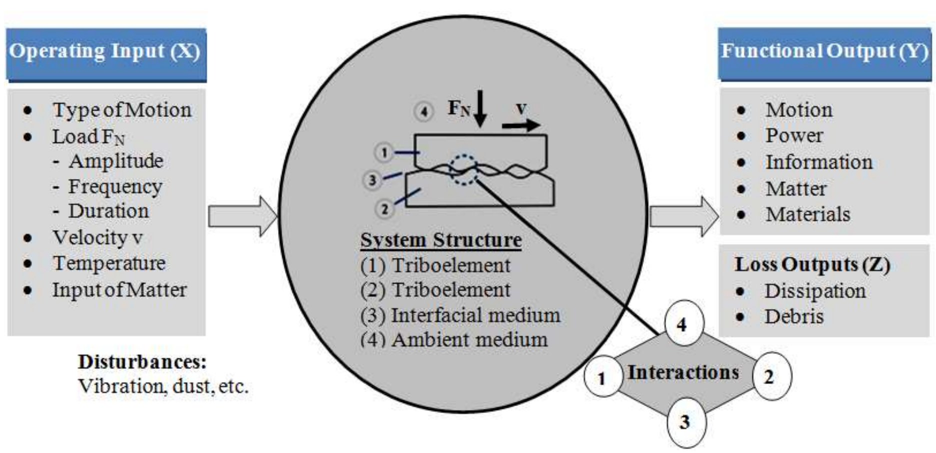

Figure 1. Function of tribological system set-up.

The difficulty in tribological system is that the friction and wear values cannot be easily transferred from a tribological testing rig to a real application. The wear and frictional property of the materials may only be estimated for specific applications in terms of modeling and simulation testing. The tribological testing allows us to gain information about the wear performance of materials under various conditions to put into practice as a better material design. Furthermore, the tribological test results give us to understand different variables such as material compositions, filler, weight fraction, synergetic effect, material structure as well as the other system elements.

The tribology also improves the efficiency and extend service life of any wearing or bearing materials providing that the critical factors affecting the tribo-system are determined and optimized the contacting surface by selecting right material combinations of low wear and friction. Moreover, a good tribological setup should be included as the following elements like reduction in cost, environmental awareness and material savings.

2. Experimental

2.1 Properties of composite materials

Properties of the composites depend on intrinsic properties like structural arrangement, interaction between the constituents, volume fraction, its orientation, matrix/reinforcement's properties, microstructure, reinforcement's shape and size, their distributions in the microstructure and isotropy of the system [1]. Such properties like elastic modulus, shear modulus, hardness, poison's ratio, friction coefficient and thermal expansion coefficient can be predicted in terms of these properties. Table 1 indicates the epoxy reinforced with carbon fabrics (CF) and basalt fabrics (BF) and its some mechanical properties such as flexural strength and flexural modulus, hardness and impact resistance [10].

The hardness increased significantly from 41 HRB up to were 91 HRB. The improvements in 40 wt% CF, 60 wt% CF composites in comparison to epoxy matrix were about 105%, 122%, respectively. In addition, flexural strength and modulus in addition to impact resistance increased considerably due to including carbon reinforcement in the form of fabrics. The flexural strength increased by about 743% because of an achievement of a strong bonding between the fibers and the matrix. However, the improvements in BFs for 40 wt% and 60 wt% in comparison to epoxy resin were about 17%, 47%, respectively. This is related to the individual fiber strength and interface bonding between the fibers and matrix.

2.2 Wear of polymeric composite materials

Wear is the gradual losses of substances from the operating surfaces of any tribo-system, which is a complex phenomenon since real contact area between two solid surfaces is too small when compared to apparent area, but the localized forces can be very large because the load applied to the surface will be transferred through these contact points. To determine the wear rate or friction, material surface property, surface finish, load, speed, temperature and counter face are very important. Wear can be measured based on the weight loss or volumetric wear rate. Material factors are called as intrinsic material properties such as reinforcement type, size, shape and distribution, matrix type, microstructure and volume fraction [1,11,12,13]. Effects of different factors on the wear rate of Polymer Matrix Composites (PMCs) are discussed as the following sections.

2.3 Microstructure of the composites

Figure 2 shows the microstructure of a 60 wt% CF-reinforced epoxy composite developed with hand lay-up method recently by Scanning Electron Microscope (SEM) image at lower magnification, exhibiting both parallel and cross-sectional view [10]. This lower magnification image includes some porosity in the fabrics and epoxy matrix due to the pressure level and mixing ratio of epoxy resin/hardener. However, distributions of fibers and matrix under increased magnification seemed to be uniform (Figure 2(b)). Interface bonding also good at this micrograph due to selecting an appropriate matrix for this combination. Further, there are no debonding between the fabrics and the matrix at higher magnification in addition to exhibiting fiber distributions in the matrix.

Table 1. Epoxy composites including carbon/basalt fabrics and its some mechanical properties [10].

Tested Mater.	Code	Weight fract. (%)	Flex. strength (MPa)	Flex. Modul. (GPa)	Rockwell B Hardness (HRB)	Impact energy (J)
Epoxy	EP	0	83	3.43	41	2.4
40wt% CF	CF40	40	601.9	38.68	84	8.6
60wt% CF	CF60	60	700	41.48	91	13
40wt% BF	BF40	40	315	16.78	48	15
60wt% BF	BF60	60	359	18.36	60.3	16.8

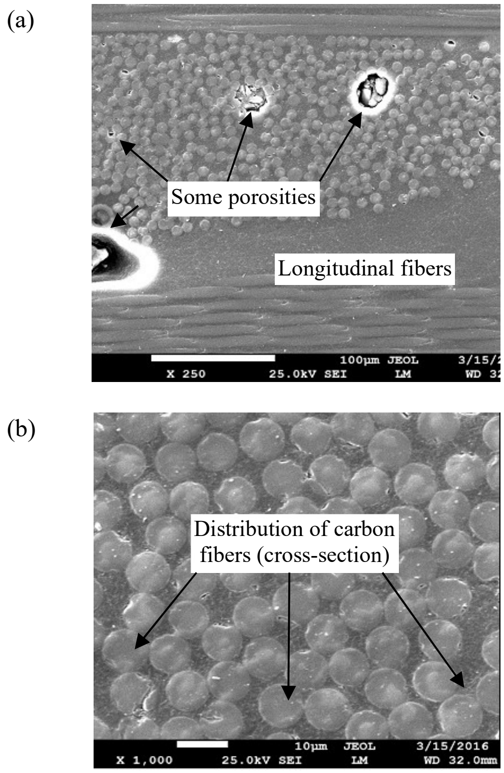

Figure 2. Microstructure of a carbon fiber-reinforced epoxy composite (CFRC). (a) Lower magnification SEM image, exhibiting some porosities and two orientations, (b) Higher magnification, indicating uniform distributions of fibers.

Figure 3 indicates a microstructure of fiber reinforced epoxy composites, which are including two weight fractions (wt%) of an unidirectional carbon fibers through SEM [10,11]. SEM shows a cross-sectional of fibers and epoxy, but it does not cover any porosity in the structure at the lower magnification. SEM photography in Figure 3 (a) indicates the distributions of carbon fibers in the matrix seemed not to be very uniform, which is the unidirectional reinforced carbon epoxy composite containing 42 wt% reinforcement (CU42). However, Figure 3 (b) exhibits that the fiber distributions in the resin seem a more uniform because the carbon content is about 52 wt% in the composite (CU52) in spite of the fact that its dimension is the same with the previous one.

Figure 4 (a) and 4 (b) shows the microstructure of a 60 wt% CF-reinforced epoxy composite containing a 2.5 wt% nano Al_2O_3 particles by SEM. This micrograph consists of both unidirectional and cross sectional of fabric layers, and formations of some craters in the structure. This cross-sectional view of microstructure is indicated in Figure 4 (b) under an increased magnification. A distribution is found to be uniform, but most of the fibers fractured from the ends are observed because of their brittle and fragile behavior of nano Al_2O_3 particles in the matrix. This higher magnification shows the fractured fibers and a good interface bonding between the fibers and resin. A similar microstructure is observed with parallel and vertical fabric's layers of 60 wt% CF fabric-reinforced epoxy composite but containing a 2.5 wt% PTFE particle [11]. That higher SEM image also indicates a formation of well interface bonding between the fibers and the epoxy resin.

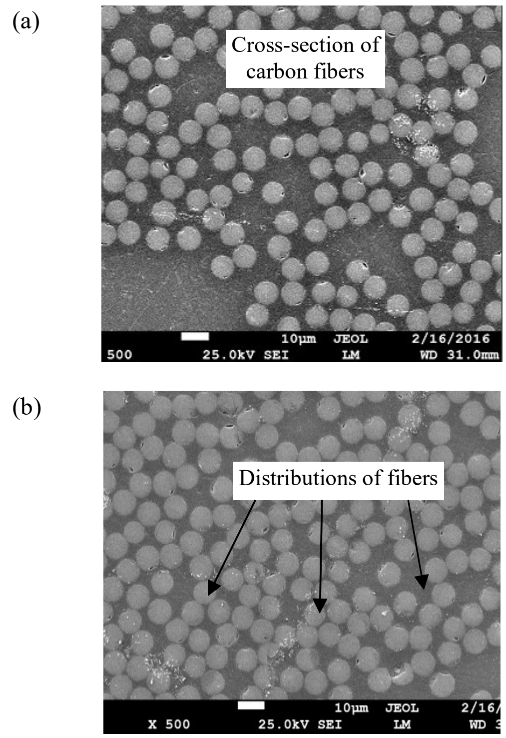

Figure 3. Micrographs of CFRC. (a) CU42 composite, showing cross-sectional view of fibers, (b) CU52 composite, indicating the distributions of carbon fibers in the resin [11].

Let`s look at the different types of composites reinforced with various sizes of the particulates. In these composites, micro-particles such as SiC and Al_2O_3 are used for making composites as reinforcement elements to find out the effects of reinforcement type and particle content on abrasive wear and mechanical property of the epoxy composite. Therefore, Figure 5 indicates a typical microstructure of particle-reinforced epoxy composites (PRCs) produced by a mixing method currently. These microstructures contain a 10 wt% SiC and Al_2O_3 particles in addition to nano PTFE particles. Figure 5 (b) shows an enough interface bonding between the fibers and the resin under higher magnification. Thus, the lower weight loss was obtained for this composite. Figure 5 (c) indicates a 10 wt% Al_2O_3 and PTFE particles in the structure. However, Figure 5(d) exhibits some porosities in the epoxy resin at higher magnification, which resulted in higher weight loss of the composite [12].

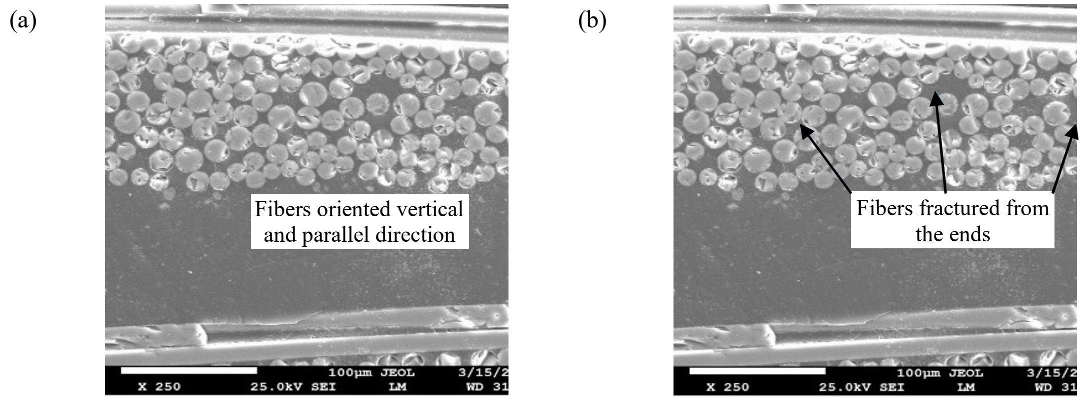

Figure 4. Micrographs of a 60 wt% CFRCs containing a 2.5 wt% Al_2O_3 nano particles. (a) Lower magnification, indicating parallel and cross-sectional view, (b) exhibiting the fractured fibers from the ends.

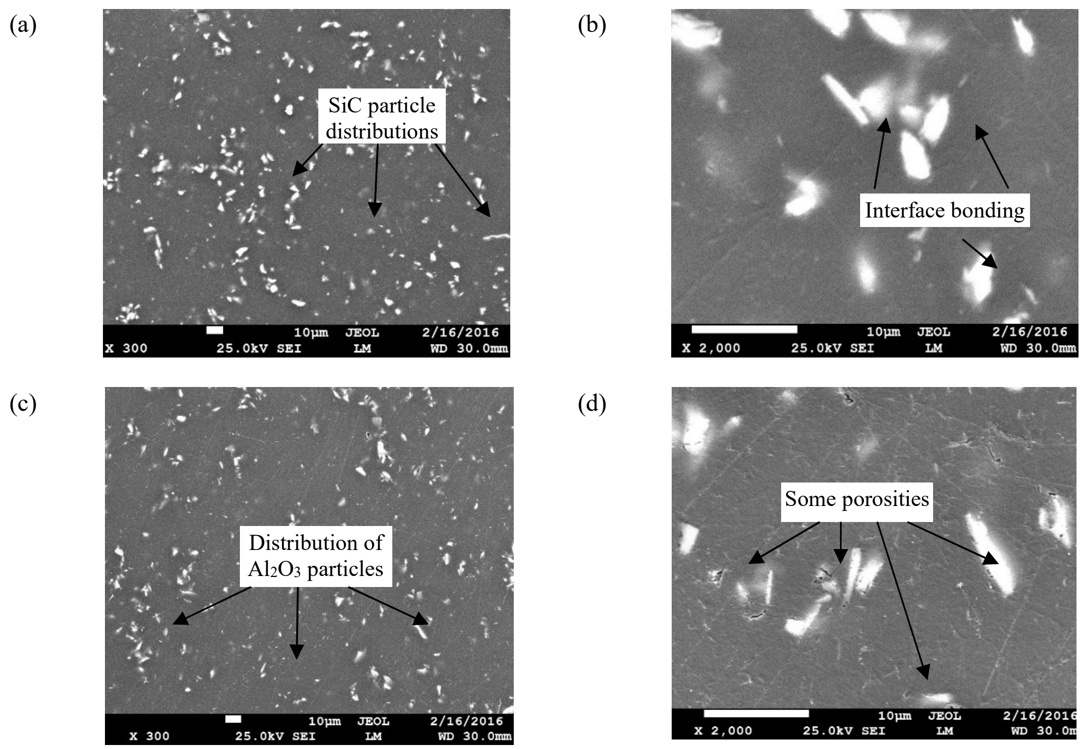

Figure 5. Microstructures of particle-reinforced epoxy composites (PRCs). (a) 10 wt% SiC&PTFE particles, (b) showing an enough interface bonding under higher magnification, (c) 10 wt% Al_2O_3&PTFE particle, and (d) exhibiting some porosities in the epoxy resin under higher magnification [12].

2.4 Effect of extrinsic factors

2.4.1 Applied normal load

The wear rate of the composite is affected with load significantly, which obeys the Archard's law. Variations in coefficient of friction (COF) versus number of cycles at a 42 wt% unidirectional fiber-reinforced composites were reported at fixed speed and load against the smooth steel. The static and dynamic COF were about 0.42, 0.17, respectively [11]. COF decreased because of decreasing the running-in period considerably. COF of the composites under 90 N load decreased from 0.45/ 0.17 was about 0.35/0.13 for static and dynamic component, respectively. After running in period, COF of Polyetheretherketone (PEEK) composite against steel was stabilized [14]. Namely, COF is measured at 0.18 for PEEK-CF30 composite while COF is about 0.21 for PEEK. However, COF increased when the conditions changed. Initial COF recorded was 0.65 for the epoxy [15] while it was 0.74 for carbon fiber composite.

Friedrich *et al.* [16] studied that COF of Polyamides (PA66) composites with and without nano-TiO_2 were abruptly reduced after an initial stage of the contact period about an hour. COF decreased with increasing a higher load due to reducing the ploughing component and frictional heat. Koh *et al.* [17] investigated the effects of load on the tribological property of silica-filled resin composites. COF and the wear property were better for the composites. The volume loss tended to increase nonlinearly with increasing the sliding distance and particle diameters. COF and wear rate increased significantly with increasing the load [18]. However, COF decreased with the increasing normal load for glass fiber, nylon and PTFE [19]. The wear rate increased with the increasing load for tested materials, but at lower load, large fluctuations occurred [19,20]. COF for carbon fiber/epoxy matrix composites showed that COF varied from 0.10 to 0.25 [21]. However, COF varied between 0.45 and 0.65 for graphite/epoxy composite and carbon/PEEK composites, respectively [22]. The carbon fiber decreased the wear rate for nylon while transfer film was formed by nylon and its 10wt% Molybdenum sulfide (MoS_2) composite [20,23], but the aramid fibers did not exhibit the fracture of fiber ends due to their toughness.

2.4.2 Sliding speed/distance

The wear rate increased for all the materials when increasing sliding speed/distance [24,25]. However, at higher velocity, lower wear was obtained for the polymer composites because transfer layers formed at the wearing surfaces. This transfer layer increased when the velocity was increased. Nuruzzaman *et al.* [26] investigated the COF and wear rate with speeds against stainless steel rubbing with various composites such as cloth reinforced ebonite, glass fiber composite, nylon and PTFE. The results showed that tribological property increased with the increasing the speed for all type of materials due to shear force and thrust force. These results indicated a good agreement with the Suresh *et al.* [23]. However, COF of nylon and wear rate of PTFE was the highest while COF and wear rate depended on the speed. The influence of SiC and graphite fillers on the wear of the epoxy composite at dry sliding indicated that COF increased with subsequent increase in load/velocity. The lower COF was observed for graphite filled Glass-Epoxy (G-E) composite, but the minimum wear rate was obtained for SiC filled G-E composite. Frictional behavior of woven-glass epoxy composites filled with Al particulates under various dry conditions showed that the frictional property depended strongly on combinations of filler content, speed and load [27,28]. On the other hand, the wear loss increased with increasing the speed and load [29, 30]. Introduction of a smaller amount of Al particles reduced the weight loss. The wear characteristics were studied for various abrading distances up to 1 km using silica sand at fixed load [29]. The wear resistance increased when alumina, silica, and alumina tri-hydrate nano fillers introduced, and the wear rates decreased under abrasives when increasing the abrading distances.

2.5 Effect of intrinsic (material) factors

2.5.1 Reinforcement size

The introduction of the reinforcements increased the thermal stabilities and improvements in abrasion and sliding wear properties under the increased temperatures [11,30-32]. The stiffness and strength properties of the composites improved with increasing the graphene contents because of higher elastic modulus/ hardness [33,34]. The frictional behavior of the composites decreased with increasing the graphenes because of the solid lubricating effect. A significant improvement was achieved for mechanical and tribological behavior of the composites owing to the graphene introduction [35]. Glass fabric reinforced epoxy (G-E) with various contents and Silicon Dioxide filled G-E (SiO_2-G-E) composites indicated that Silicon Dioxide filler reduced the wear of G-E; but optimum wear rate was obtained for 10 wt% of SiO2 filler loading [36].

Mohan *et al.* [37] studied the wear behavior of hard particle reinforced glass fabric epoxy reinforced hybrid composites. There was a significant reduction in the wear rates as introduced SiC filler into glass/ epoxy composite because of lower damages on fibers. The particles in localized areas of high stress concentrations affected the flow stress and wear rate [38]. The lowest wear rate was observed from fine, well-distributed particles in the microstructure. The wear resistance was improved due to reducing the carbide's size. Zsidai and Katai [39] showed that a better wear resistance was provided for the short carbon fibers to PA6 and PEEK when compared to short glass fibers.

2.5.2 Reinforcement types

Gupta [40] made a comparison study between chopped and bi-directional glass fiber reinforced composites. It was found that the chopped glass reinforced composites had a better wear resistance than that of the bi-directional glass reinforced composite at abrasive sliding wear conditions. The introduction of polytetrafluoroethylene (PTFE) and graphite in bi-directional glass (G) fiber and basalt (B), G-B/E hybrid composites had a considerable effect on the tribological property at various distance/loads because of achievement a better adhesion and well distributed particles in the epoxy [41]. Moreover, lower wear was obtained for PTFE filled G-B/E composites in compared with graphite filled G-B/E hybrid composites. Tribological properties of carbon-epoxy (C-E) composite and glass-epoxy (G-E) composites indicated the lower COF and wear loss when compared to G-E composites [42]. Effect of SiC filler in different wt% on wear rate of chopped G-E epoxy under abrasive wear exhibited that void fraction decreased with the adding SiC content up to some extent. In addition, the wear resistance increased with increasing the sliding velocity for whole wt% reinforcements and the wear rate increased with the increasing the load, whereas, the wear rate decreased for all normal loads when added SiC with different weight fractions.

Tribological behavior of PTFE-Cotton fiber filled with Titanium Dioxide (TiO_2) nano particles and modified TiO_2 nano particles showed that the lowest COF was observed for unfilled sample, followed by 5 wt% TiO_2 sample and hybrid composite [43]. A sudden rise in the wear rate was appeared as tested at 219 N load. The wear properties improved with increasing loads because of the grafted polymers. The frictional properties of ultra-high molecular weight polyethylene (UHMWPE) composites reinforced with basalt fibers up to 20 wt% under 240 N load exhibited that COF stabilized at a sliding time of 50 min [44]. COF of 0.26-0.28 was obtained. The wear resistance of the composite increased significantly when the wt% of fibers increased since amounts of spherical and pole like debris increased. Patnaik *et al.* [45] studied an epoxy resin reinforced through Al_2O_3, SiC and pine bark dust for glass fiber reinforced epoxy composite. The abrading distance was more effective than the speed. Similar result was found for Reference [44], but SiC particles indicated a better tribological behavior of glass-epoxy composite. The graphite fillers led to improvements of abrasive wear property of carbon reinforced composites (C-E) highly [46,47]. Further, wear property was better for B-E composite in comparison to G-E composite when subjected to abrasion tests [47,48].

Frictional and wear property of polyester matrix reinforced with different fibers or fillers like carbon and coir under dry sliding conditions showed that COF of carbon fiber reinforced polyester decreased to 0.48 for fiber content up to 25% [49]. Increase of carbon powder to 25%, COF decreased to 0.32 for the carbon filled polyester composites. However, the wear rate decreased with increasing carbon fiber or powder. Moreover, an increase of coir powder decreased the COF of polyester composites.

2.5.3 Volume/weight fraction

The wear property of polymer composites could be improved by increasing the volume fraction of reinforcements at dry conditions [1]. The volumetric wear rate decreased with increasing the volume fraction of the fillers because of dropping in ductility. The tribological behavior of Carbon Fabric Reinforced Polymer Composites (CFRCs) investigated at various conditions was shown in Figure 6. The wear rate considerably decreased with the incorporation of the reinforcing carbon [11,50]. The reinforcement contributed strongly to the wear resistance of the composites in spite of the fact that the friction properties deteriorated. This can be caused by increasing the mechanical strength. The wear rate increased with increasing the load.

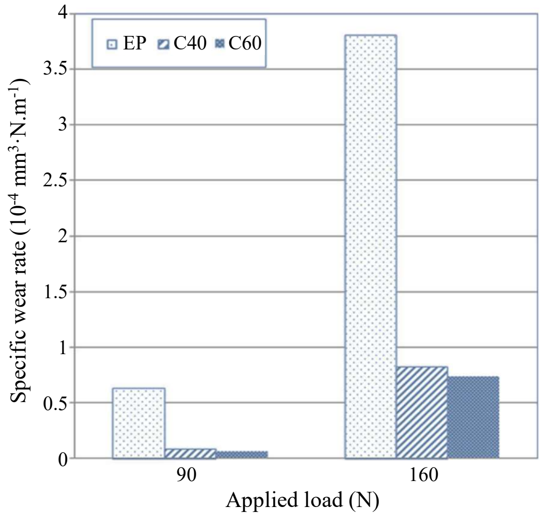

Figure 6. Average wear rates versus load for CFRCs, rubbed at 0.42 $m \cdot s^{-1}$ speed [50].

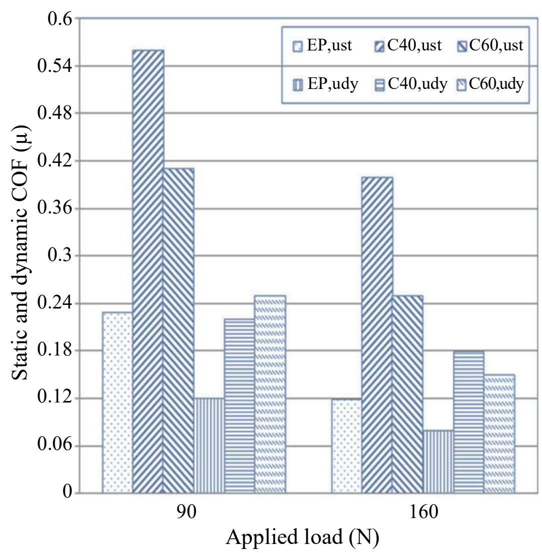

Figure 7. Variations of static and dynamic coefficients of friction for CFRCs composites, sliding at 0.42 $m \cdot s^{-1}$ speed and different loads against the hardened steel [50].

Graphite filler (3-5 wt%) increased the wear resistance of cotton fiber reinforced polyester composites [51]. Similar works related to other reinforcements/particles such as glass fibers, SiC and SiO_2 fillers played a significant role for controlling the wear rate of the composites [52-56]. Moreover, COF for the composites decreased with increasing the load (Figure 7) [50]. The same trend was observed for CF40 composite with increasing slightly. For example, static COF of CF60 equaled to 0.40 and 0.25 for 90 N and 160 N, respectively. The average COF for the composites equaled to 0.49 as static and 0.24 as dynamic at a load of 90 N. On the other hand, COF of the epoxy equaled to 0.23, while COF of CF40 and CF60 specimens equaled to 0.56 and 0.40, respectively. The erosion wear resistance increased with increasing volume fraction of coir dust reinforced polymer and decreased with increasing the load [57]. However, the frictional behavior of the composite was deteriorated when used a higher weight fraction of fibers [58,59]. Raju *et al.* [60] concluded the alumina filled G-E composites containing 10 wt% was prepared, and introduction of Al_2O_3 reduced the wear rate of G-E composite, but the wear property was excellent for Al_2O_3 filled G-E composites [61].

2.6 Fiber orientation

Several researchers have studied the effect of fiber orientation on the tribological aspects. The most of the works on friction and wear properties of polymer composites were based on two options; these are either normal (N), parallel (P) and anti-parallel (AP) to the sliding directions; or randomly orientated or unidirectional orientated fiber composites. Some of the results are contradictory in nature. For example, Alshammari *et al.* [62] showed that the wear resistance of AP orientation was better, followed by P and then N orientation [63-66] while other works indicated that a better wear resistance was achieved with P orientation [67-73]. However, some other studies indicated the N orientation was better [74-75].

2.7 Mechanisms of increasing wear resistance and reducing friction coefficient

The dry wear tests of the polymers/metal/composites are carried out on various pin-on-disc types of tribometers. The friction coefficient, μ and wear rate, Ws are calculated from the following equations (1, 2).

$$\mu = \frac{F}{N} \quad (1)$$

where F is the frictional force and N is the normal load acting on the system.

Specific wear rate is determined by the mass loss of the specimen after the test, according to the following equations:

$$Ws = \frac{W}{\rho} = \frac{\Delta m}{\rho.N.L} \quad \text{or} \quad (2)$$

$$Ws = \frac{\Delta V}{N.L} \ (mm^3 \cdot N.m^{-1})$$

Where Δm is the mass loss of the specimen, ρ is the density of the specimen, N is the normal load applied on the specimen during sliding, L is the total sliding distance, ΔV is the volume loss, and w is the dimensionless wear rate (unit length/unit length). The specific wear rate is considered as a material property or wear factor, K. The wear resistance is described as 1/Ws. The mechanical properties, tribofilm and debris formation affect the wear resistance of the composites.

Coefficient of friction of the composites can be reduced with the following factors [76]: (a) inclusions of solid/soft fillers, (b) applying the external lubrication, (c) selecting an internal/intrinsic lubrication. When you put the soft fillers in the matrix, COF is reduced because soft filler and matrix acts as a lubricant and generating a transfer film at the interface between the filled polymer and steel counter face. On the other hand, coefficient of friction, μ is consists of two components, namely one is adhesive component, μ_a and other is deformation component, μ_d but $\mu = \mu_a + \mu_d$. It can be remembered that the higher modulus of elasticity of material results in less deformation. Thus, μ_d is reduced and leading to the smaller real contact area, A_r is between the mating surfaces. Consequently, μa also is reduced ($\mu a = \tau_S.A_r/N = \tau_S.A_r/F_N$). Some people take N force equals to F_N force. Where τ_S is the shear strength of material, Ar is the real contact area and N is the normal load. In addition, thermal conductivity is also another important factor affecting the wear and friction coefficient of the composites.

Fibers/filler particulates in the composite affect the friction and wear properties of polymer composites. The improvement in the wear behavior of polymers when adding the fibers/particulate into the matrix was achieved due to greater load carrying ability of the fibers or particulates than the matrix due to their much higher strength and stiffness. Between two, fibers are more effective than the fillers because of their higher aspect ratios that are achieved an increased interface bonding between the fiber and the matrix. The resistance to surface damage in fiber/particle during sliding wear process can be obtained due to increased shear strength [77]. In other words, the more smoother surface was observed with adding the fiber reinforcement and this led to increasing the wear resistance of the composite.

2.7.1 PV factor

To develop wear resistance materials for tribological applications, it is important to evaluate and understand the effect of different contact pressure x sliding speed (*pv)* conditions and environment conditions. As shown in the previous section, the increase of speed and load mostly affected the friction and wear properties of polymer composites due to increasing the contact temperature, but high pressure leads to changing the wear mechanism. Greater contact temperature also reduced the shear strength of the matrix and this resulted in an increased the wear rate [78]. However, when increasing the high pressure, friction coefficient tends to decrease because of thermal softening effect on polymer and its composite.

Frictional measurements carried out on PEEK polymers against steel/sapphire showed that coefficient of friction decreased linearly with increasing the load, which is inconsistent with Amonton's law, due to increasing the real contact area [79]. It is also noted that strongly adhered debris formed on the steel surface.

It is reminded that the friction is related to both the elastic-plastic deformation and adhesion of sliding surfaces. In addition, friction coefficient changes with speed. As the speed is low, frictional is not significant, but the contact area increased because of local plastic deformation of surface asperities, leading to higher friction. When the speed is 1 $m \cdot s^{-1}$, friction reaches maximum value then drops with the speed. This transition point is due to thermally softening or melting of polymers. For the friction coefficient of PEEK; its short carbon fiber and its graphite fiber reinforced composites, COF increased initially, which was observed for all the samples, but after run-in period, friction coefficient stabilized with the sliding distance [80]. It is obtained that once the steady state condition is reached, the coefficient friction remains stable/ constant during the test. The coefficient friction decreased with increasing load and speed because of increment in the temperature.

Chowdhury *et al.* [81] showed the coefficient friction decreased more or less linearly for polymer composites, which is not true for PTFE. However, coefficient of friction increased almost linearly as the horizontal vibration increased for glass fiber polymer composites. The mean reason for increasing COF should be regarded as [82]: (a) variations of inertia force along friction force, (b) a greater abrasive shearing and ploughing of asperities, (c) micro-welding of contact asperity, (d) increasing the material deformation because of high temperature. An increase in the *pv* factor, material firstly failures in the interfacial region. As the matrix loosen to support the short fibers, series fibers removal could occur and therefore a wear rate rapidly increased, but for the longitudinal fibers, this process takes a longer time to remove the fibers in their places because of having a long and strong interface bonding between the fibers and the matrix.

For dry sliding wear of polymeric composites, responsible wear mechanisms are matrix wear, fiber sliding wear, fiber fracture and debonding of matrix and reinforcement. Matrix subjected to high friction and micro plowing, which is gradually increased after peeling of fibers because of sliding process. These led to cracking matrix and debonding of the matrix and reinforcement. The debonding is also affected by volume fraction and fiber sizes. It increases with increasing the reinforcement sizes because of increasing the tearing or wearing of the composite surface. Thus, the wear property of the composite is primarily dependent upon the fiber breaking, fiber debonding and matrix cracking [83].

2.7.2 Transfer layers

The formation of transfer layers (TFLs) for reducing the friction and wear behavior of polymeric and its composites was an important factor. TFLs are usually formed for the sliding wear of composites when used solid lubricants such as graphite, MoS_2, and PTFE [16,19,38,84-88]. These solid lubricant materials led to forming a transfer layer on the steel counter face surface by protecting the fiber from severe abrasive wear. The development of transfer film depends on the run-in, transition and steady-state sliding periods. The transfer film in run-in period has a large plate-like debris while steady state region indicates an island-like morphology which is about 20-50 µm size. This island connects with each other with distance and finally generates a continuous transfer film.

Short carbon fibers (SCF) improve the hardness, load carrying capacity and creep resistance of PEEK polymer while PTFE and graphite were benefited for reducing the adhesion between the polymer and the steel counter face [80]. This is due to the soft nature of PTFE, which is poorly adhered to the counter face and is removed quickly as a wear debris. Zhang *et al.* [89] studied the silica nano particles on the tribological property of epoxy reinforced with carbon nanotubes (CNT), short carbon fibers (SCF) and short glass fibers (SGF). The combination of nano-silica and SCF indicated a synergetic effect on improving the tribological behavior due to generating the transfer film between the reinforcement and counter face, but no synergy was identified between CNT and silica. The well lubricating property was achieved due to basically compacted nano particles. Other study of same authors [90] revealed that a continuous transfer film, which developed in the run-in period on the steel counter face generated only over 10 wt% nanosilica/epoxy composite, reduced the wear rate. In other words, it is found that size of debris particle played a significant role for 20 wt% silica/epoxy composite for the formation of transfer film because smaller debris are easily compacted layer.

The influences of nano-filler on the tribological behavior are found to be more effective than micro/ macro reinforced composites [16,77,91-92]. These were due to the higher surface-to-volume ratio of nanofillers, which provides the more interfacial areas.

2.7.3 Failure mechanism

Addition small amounts of nano particles such as graphite to SCF+PTFE/polymer composites and nano TiO_2+graphite to SFC+PTFE/polymer composites improved the wear and frictional properties significantly, particularly under high *pv* conditions, as shown in Figure 8 [93]. These nano particles reduced the adhesion between transfer film and the polymer sample by decreasing the real contact area, leading to a lower friction. The distance between the steel and the composite is improved, particles can be acted as "spacers", leading to reduce the adhesion. Thus, coefficient friction is always lower for the nano composites than that of the composite without nano particles, as shown in Figure 8 (b).

Moreover, the addition of 5 vol% nano-TiO_2 on short fiber reinforced epoxy composite is investigated under high *pv* conditions. The wear rate and friction coefficient significantly reduced due to three-body contact/rolling effect [16,91]. The addition of nano scale CuO and short fibers to polyphenylene sulfide (PPS) led to the formation of thin and uniform transfer layer in comparison to the unfilled PPS and CuO filled PPS composite [77, 94-97].

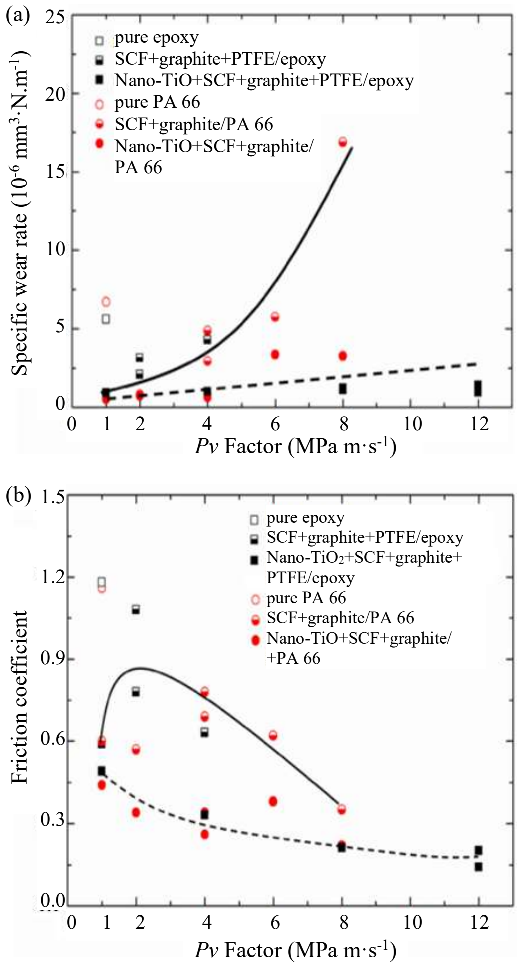

Figure 8. Wear results of various polymeric composites at different sliding conditions. (a) specific wear rate, (b) coefficient friction. Dashed lines: wear results of the composite with nano particles, full lines: wear results of composite without nano particles [93].

Figure 9 shows a schematic illustration of the failure mechanisms during sliding wear of SCF composites without nanoparticles. Fiber diameter is too small relative to surface roughness of the steel counter face. During this process, the short fibers carry the most of load and wear against the counterpart. The worn surface can be smooth with low load condition. When the *pv* increases, breakage of the polymer occurs in the interfacial region around fibers because of the high friction and heating. Due to this reason, the fibers are removed more easily since the local support of matrix is lacking. Consequently, the wear rates of the composites are progressively increased.

Figure 9 (b) indicates a schematic illustration of the failure mechanisms during sliding wear of SCF composites with nanoparticles and contact mode for the SFRP composites and force analysis for a single nanoparticle with a radius of R, respectively. Fiber diameter is too small relative to surface roughness of the steel counter face and size of nano particles.

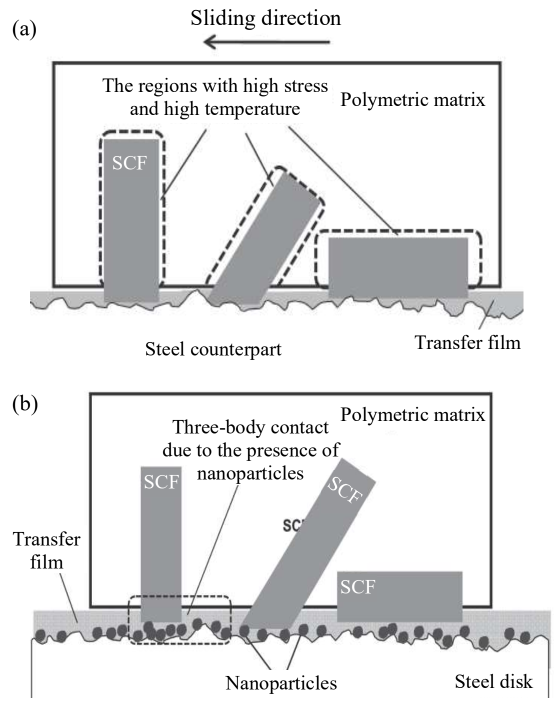

Figure 9. Schematic illustration of the failure mechanisms during sliding wear of SCF composites without nanoparticles [93].

For the case of nano composites, however, the situation was much more different. As shown in Figure 10 (b) and Figure 10 (c), the worn surface observed much smoother even at heavy conditions because the fibers are always removed gradually from its place and fully contributed to the wear resistance of the composites. Therefore, the wear rate of the composites was much more stable, as indicated in Figure 10 and load carrying capacity of the material was considerably improved. Furthermore, with the addition of nano particles to polyamide composites, a smoother surface was observed and resulted in much lower wear rate [89,93].

Figure 10 (a) indicates the wear surface of the neat epoxy resin. This surface was roughly worn and deformed area, arrow indicates sliding direction. Figure 10 (b) shows the wear surface of epoxy-SiC composite (5 μm, 17.5 vol%), indicating multiple-grooves and compacted layers over the surface while wear surface of epoxy-TiO_2 composite (300 nm) shows a few wear grooves [94]. Thus, smooth surface was observed because the delaminating type, plate-like wear was evident. As a result of this, EP-TiO_2 showed the lowest wear. Sliding direction is shown by arrow.

Figure 11 shows the SEM graphs of worn surfaces of 10 vol% SCF composite and 10 vol% SCF/3SiO_2 nano composite under high magnification, respectively. Figure 11 (a) indicates numbers of micro-sized cracks oriented perpendicular sliding direction are observed near to carbon fibers, but there was a stress concentration effects in vicinity of the fibers in spite of the fact that the most of the load was carried by SCFs fibers to epoxy matrix [99]. Figure 11 (b) shows the worn surface of nano composites, but no micro cracks were observed on the worn surface of 10 vol% SCF/3SiO_2 nano composites. This might be due to dispersing of nano particles in the matrix and thus, stress concentration was alleviated near the fibers. It is shown that thicker TLs are generated for the polymer at higher speeds, but thin layers were formed at larger loads [100].

(a)

(b)

(c)

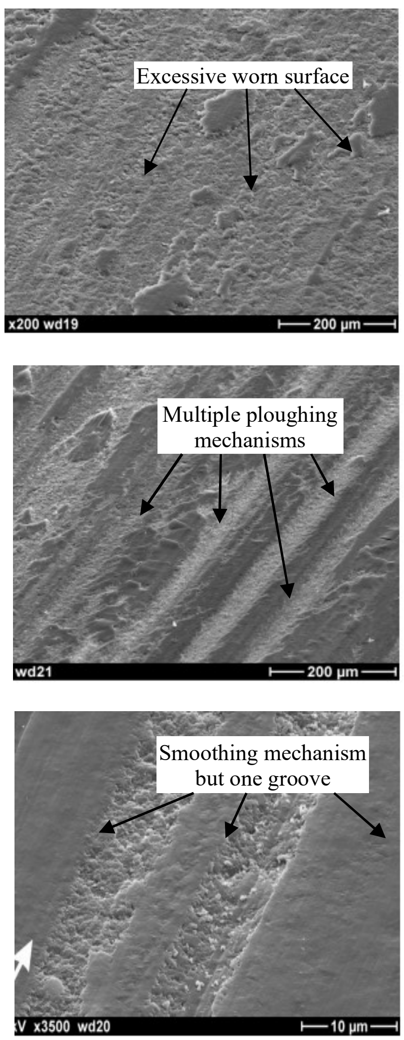

Figure 10. Worn surface of the neat epoxy resin, showing worn and ploughed areas (a). Worn surface of epoxy-SiC composite (5µm, 17.5 vol%), indicating multiple-grooves (b), Worn surface of epoxy-TiO_2 composite (300nm), showing a few wear grooves (c) [94]. Arrow indicates sliding direction.

(a)

(b)

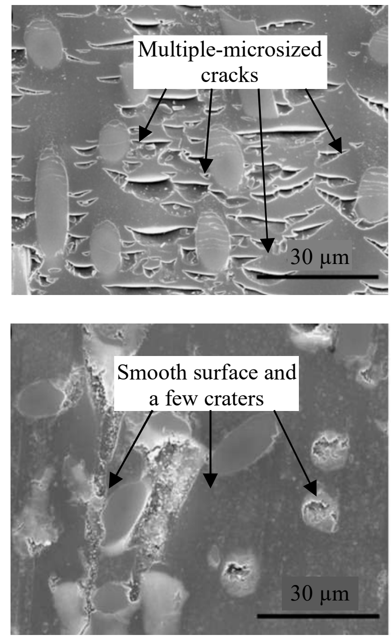

Figure 11. Worn surfaces of the composites at high magnification. (a) 10 vol% SCF composite, indicating multiple micro cracks over the sample (b) 10 vol% SCF/3SiO_2 nanocomposite, showing smooth surface and a few craters [89].

For higher surface roughness of mating pairs, there was a more debris to fill up the valleys. After having filled the valleys with the debris, generated continuous TLs, but if the detachment of large chunk of TLs come up a high wear rate took place. Recently a number of studies has indicated that graphene is widely used for making the composites using polyamide and PTFE, UHMWPE to improve the tribological behavior because it is two-dimensional crystal consisting of carbon atoms, which is combined with large surface areas [101-105]. The improvement in wear property of the composites was because of self lubricating property and easily generating the transfer layers on the steel counter face.

In general, TLs are gradually developed on the metallic counterpart during the initial running-in stage [106]. In the steady state region, the tribo-contact changes from the initial hard (rigid fillers)-on-hard (asperities of steel), to hard (rigid fillers)-on-soft (polymeric TL), or soft (polymer)-on-soft (polymer TL) mode. Therefore, the contact mode depends on the spreading and quantity of TLs in the real contact points.

Transfer layer thickness (λ) can be calculated in the following equation 3 [106]:

$$\lambda = \frac{t}{Ra} \quad (3)$$

Where t is the average TL thickness (t, which is also equal to nano-indentation hardness of the sample) and Ra is the surface roughness of the steel.

If the λ is lower than 0.2, the contact is considered as insufficiently lubricated as there is not TLs to completely cover the steel counter face. In this case, wear behavior greatly depends on the sliding conditions like *pv* factors, as described in section 2.3.1. If *pv* value is small, it is likely to shield the surface efficiently, even with thin TLs because of a small actual contact area. However, under higher *pv* conditions, actual contact area rises, and additional fillers/fibers are exposed to steel counter face with insufficient shielding from TLs. The contact type would be in the form of "hard-on-hard", resulting in a high friction coefficient. When the λ is over 0.2, TLs is adequately lubricated layers where they are capable of shielding most of the fibers /fillers from the direct contact with the steel counter face for both high and low *pv* conditions. Wear behavior is determined by a combination of two contact modes. These are: polymer contact against TLs (soft-on-soft) and hard fillers contact against TLs (hard-on-soft). Due to shielding of TLs, severe fillers pull out might be evaded even at high *pv* conditions.

Nonetheless, if the quality of TLs is very high, it can be resulted in high wear rates. In this case, TLs can be break down in the form of large chunk of wear debris as relatively thick, TLs could act as thermal insulators on the steel surfaces. Hence, localized contact temperature in that thick TLs are might be high and may cause strong adhesion between the polymers and TLs. On the other hand, high contact temperature may also decrease the viscosity of polymeric TLs, which subsequently, results in a small friction coefficient. In the case of the thickness of the TLs is greater than the surface roughness of the steel counter face, the effect became more considerable.

Another important issue is to change the environment conditions like water, liquid or temperature etc. which affects the tribological property of polymeric composites. For example, Gao *et al.* [98] and Yamamoto *et al.* [75] studied the glass fiber reinforced composites under water condition. They were concluded that COF decreased in all testing conditions, but wear rates increased. Similar work was carried out by Kurdi *et al.* [91] on the PEEK based composites reinforced with different TiO_2 contents. The results indicated that COF decreased in the presence of water, while wear rate increased significantly because the degradation of polymer structure due to molecule absorption.

2.8 Prediction of tribological properties

For all industrial fields, loss of material becomes an inevitable owing to the relative motion of two sliding contacts. When the extent of material's wear is over a critical limit, catastrophic failure of the machine components may occur by causing to large economic losses. Thus, wear predictions is extremely important for the industrial practice in order to avoid massive financial losses because of the wear. The wear property of the polymeric composites is studied [56,107].

2.8.1 Taguchi design

Taguchi method was applied for wear behavior of polymer matrix composites [57, 108-122]. It can be seen that the grit size was pre-dominant parameter on the wear properties [109-114], followed by the load [12]. The wear rate decreased with increasing the running distances [113,116], but it increased slightly with the filler type [117]. Taguchi's analysis also indicated that the most significant effect was the normal load, but the least significant effect was the speed on the wear property of filled epoxy [109,111]. Furthermore, filler contents and interface bonding played a significant role in reducing the wear. The weak bonding between the particles and the polymer caused a significant increase in the wear rate [5]. Taguchi L27 method and analysis of variance (ANOVA) were used to identify the effect of process parameters on the wear of PTFE based composites [107]. The sliding distance had the greatest effect on the wear, followed by load. On the contrary, the load affected the wear behavior of PTFE glass-filled composites was stronger than the sliding speed [108,110-118], but the speed had a stronger effect on the wear rate of glass-filled polymer composites.

It was revealed that the effect of variables (PV) factor and filler content [116-122] was more pronounced on the sliding wear of glass-vinyl ester composites. Tribological property of 60 wt% carbon fabrics containing up to 5 wt% alumina nano particles fabricated by mixing method associated with compression molding method was investigated using a Taguchi method by taking into accounts of nano addition, load, speed and grit size [113]. Among the control factors, the grit size had the largest effect on the wear resistance because of increasing the cutting ability of SiC for the composite, but the load factor and the speed factor were followed, respectively.

Furthermore, the increases in the weight loss with grit sizes changed linearly because the sizes of SiC abrasives decreased from 800 meshes to 360 and 180 meshes, which are corresponded to about 15 μm, 38 μm and 84 μm, respectively. As a result of these, cutting abilities of SiC abrasives increased significantly, hence leading a higher weight loss. However, it decreased slightly with increasing nano-addition to the epoxy composite. It is worth to note that the nano's sensitivity was lower than that of the speed and load. The filler contents and grit sizes exhibited the most significant factor on the tribological properties of the polymer composites at abrasive condition, respectively [116-118] and [109-113]. Moreover, the different heat treatments are applied on the pultruded kenaf fiber-reinforced polyester composites using Taguchi approach [122]. The flexural strength and modulus of the heat-treated samples indicate a better performance at 140°C.

The most significant factors that affect the wear is the counter face roughness and heat treatment temperature.

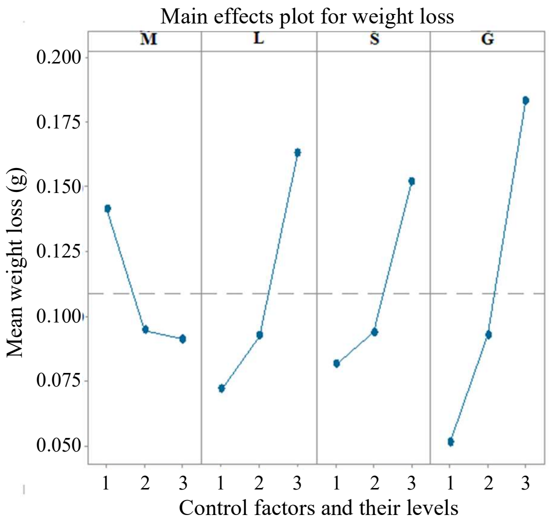

Figure 12. Average weight loss of CFRC-n composites when tested against SiC abrasives [113].

The correlations between the control parameters and mass loss of the samples were found with multiple regressions [12].

$$\text{Weight loss, WL (g)} = 0.0530 - 0.0031\,M + 0.0212\,L - 0.1860\,S + 0.0679\,G - 0.0374\,M{*}L + 0.0414\,M{*}S + 0.0599\,L{*}S \quad (4)$$

Where *WL* means is the average mass loss, Eq. (4) showed that the weight loss was increased with the load and grit size, but the mass loss decreased with the nano addition and speed. The coefficient R^2 was 96.6%. The estimated weight loss of CF60 fabric-reinforced epoxy composites was calculated using Eq. (4) with the substituting the recorded values of the variables. The predicted dry weight loss was found to be very close to the actual values in generalizing system characteristics by the predicting values the difference between verification and calculation was about 4.25% [11,12].

2.8.2 Response surface methodology (RSM)

The wear and frictional properties of different polymers covering Al_2O_3 and PTFE nano powders were studied using Response Surface Methodology (RSM) [109,124-133]. The highest effect was the load, followed by the speed factor and the material's type factor, respectively. In other words, the wear rate decreased remarkably for both nano-addition effects. The wear rate increased linearly with sliding distance for all tested materials including resin and glass, graphite fiber reinforced polymeric composites [123]. They were a good agreement with Archard's equation. Ozsoy *et al.* [127] investigated the mechanical and frictional property of glass fiber-filled composites containing various contents. The result exhibited that the applied load had the largest effect on the wear rate (52.11%) and COF (65.27%) for the composites, respectively. Other study also indicated that most significant variables affecting the wear and friction of ultra-high molecular weight polyethylene (UHMWPE) composites is load, followed by sliding distance and speed [133]. In the previous work on unfilled UHMWPE and epoxy specimens [109], load was the most significant factor. However, for the filler reinforced UHMWPE composite, the main control factor was the particle size in the composite while the speed seemed a little influence for the wear [124]. Carbon fabric reinforced epoxy (CFRCs) composites were investigated using the RSM [129]. The factor of sliding distance indicated the highest effect on the wear since SiC abrasive's penetration abilities on the steel disc continued more or less linearly with plowing the composite samples, but the load factor was more effective than the speed because of increasing the real contact area. It was contradictory to some researchers indicated that the abrading distance was more influential on the weight loss or wear. However, recent work by Şahin [126,128] showed that the great effects on the weight loss were the applied load.

The influence of SiC and Al_2O_3 particles on the microstructure and wear property of epoxy composites including PTFE particles has been investigated recently against SiC abrasives with RSM approach [12]. The microstructures examined through Scanning Electron microscope (SEM) were indicated in Figures 5 (a-d). The 10 wt% SiCp-reinforced epoxy composite revealed the lowest wear than those of others because of an achievement of a good bonding between the particle and matrix using these particles. The increase in the weight loss was more affected by the load than by the speed. Similar results were also reported on the wear behavior of the polymeric composites [124-128,130]. A mathematical model was developed to predict the wear behavior of fiber-reinforced polymers at abrasive sliding conditions [131-133].

2.9 Wear prediction for hybrid composites using RSM

Hybrid composites contain more than one fiber or one matrix system in a laminate. For example, car bumpers are made of glass/epoxy layers to provide torsional rigidity and graphite/epoxy to give stiffness. The combinations also cover the cost of the bumpers. The tribological property of the nano clay particle with natural fibers (sisal and jute), artificial fiber (glass), and epoxy resin to analyze the specific wear rate and coefficient of friction are studied under dry sliding conditions [133]. Box-Behnken design is adopted technique with influence of parameters like filler content, load, sliding distance, and sliding velocity. The experimental results indicate that the coefficient of friction and wear rates are minimized with the addition of filler content to composites. E-glass/jute fiber reinforced epoxy composites are produced with an addition of Al_2O_3 and bone powder using hand layup technique and a comparison for wear behavior of these composites is made at similar test conditions [134]. The Taguchi's (L_{27}) design is applied for three control variables including sliding velocity, filler content and normal load. The results show that the normal load for Al_2O_3 and filler content for bone powder emerged as the significant factors affecting the specific wear rate of hybrid composites. An addition of 10 wt% of bone powder or Al_2O_3 into E-glass/jute fiber reinforced epoxy composites increase the wear resistance considerably.

The optimization of wear performance of plain epoxy, epoxy/E-glass fiber and epoxy/E-glass fiber/ carbon particles composites is carried out through RSM in terms of speed, load and sliding distance [135]. Optimization is conducted for weight loss (WL) and coefficient of friction (μ), followed by development of an artificial neural model for predicting the wear performances. The experimental and the artificial neural network (ANN) predicted values are found very close and thus ANN model developed can predict the WL and coefficient of friction, μ both within the design limit. Two-body abrasive wear (2-BAW) behavior of thermoplastic co polyester elastomeric (TCE) reinforced with and without short glass fiber, filled with various fillers (polytetrafluoroethylene, silicon carbide and alumina) at different weight fractions are evaluated by RSM approach [136]. Three-factors and three-levels face centered central composite design are used for conducting tests to predict the specific wear rate of TCE composites. The results indicate that the wear rate increases with increase in fiber/filler content and decreases with increase in grit size of SiC abrasives and abrading distance. These results indicate that the fiber/filler content is the most influencing factor, followed by grit size of SiC abrasives and abrading distance.

The dry sliding wear behavior of glass/epoxy composites reinforced with titanium dioxide and graphite filler materials is studied at various conditions [137]. The Central composite design and RSM is adopted to determine the influence of control factors and their interactive effect on the wear. It is seen that applied load and sliding distance have more influence on the specific wear rate than sliding velocity. It is noticed that the wear rate is decreased with the increasing weight percentage of filler. Moreover, the abrasive wear properties of hybrid composites including B_4C, graphite/6061 and 7075 alloy, SiC/Al_2O_3, graphite are investigated using Box-Behnken Design to optimize the different factors such as sliding distance, speed and load [138]. The effect of control parameters on the wear and COF of metal matrix composites is also determined through RSM approach. The predicted results by RSM reveal the close agreement with the experimental values of the wear and COF of the hybrid composites [139,140].

2.10 Application fields

The epoxy based polymeric composite materials are nowadays finding many applications in manufacturing and automotive industries successfully because of lightness, excellent specific modulus, self lubricating property, high temperature property, vibration and resistance to corrosion environment.

Applications are generally focused on components of thin-cross-sections such as aircraft wing and fuselage sections, horizontal/vertical stabilizers, helicopter rotor blades, automobile and truck body panels, and boat hulls, which are made from Glass fiber reinforced polymers (GFRPs) and Carbon fiber reinforced polymers (CFRPs) [141,142]. Fuel thanks made up Kevlar reinforced rubber composites. In recently, wind turbine blades made of basalt/carbon fiber reinforced epoxy composites with radius up to 60 m, but BMW produces honeycomb composite with carbon fibers while CFRPs are used extensively by Formula one.

Moreover, multi-layer leaf springs, heavy duty bearings and filament wound composite bushings reinforced with continuous fiber reinforcements are made of polymeric composites in mechanical engineering applications [76,143].

2.10.1 Tribological applications

The composite bushings are made with filament winding method for harsh environments. When the working conditions occurs in harsh environment such as higher loads and vibrations associated with corrosive elements, e.g. cranes, polymer composite bushings made from filament wound method. Namely: back layer consists of high vol% glass fibers and the sliding surface made of PTFE and other polymers can bring some beneficial solutions like a good impact/vibration, well resistance to corrosion because of the increasing loading capacity up to 150 MPa. These types of composite bushings are available commercially with various dimensions (Figure 13) [144]. Polymers and polymer composites showed a self-lubricating property at dry sliding condition in frictional assembly system. Conductive polymer composites also have been developing with dispersive with conductive filler like graphene, carbon nano tube or metallic particles for using biomedical implant applications.

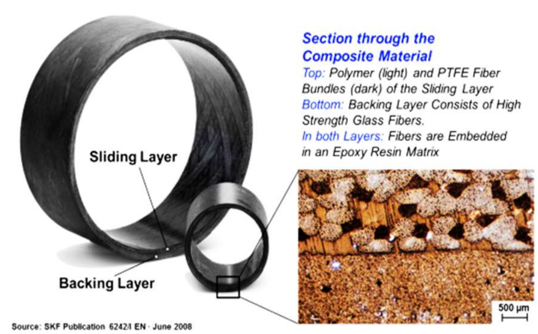

Figure 13. SKF filament wound composite bushings [144].

Applications of hydrogen in aviation and automobile industries. Hydrogen buses are produced in Munich airport, hydrogen combustion cars are made by BMW, and the former Deutsche Aerospace Airbus has worked on a model of an aircraft with a hydrogen engine [145]. These types of materials to be used for cry technical machines and plants should be more resistant to extreme conditions. These tribo-systems are characterized by special media such as gaseous helium, cryogenic liquids or vacuum. Chemical reactions can be occurred due to mechanical activation of the system for tribological applications in hydrogen environment.

3. Concluding summary

This review introduces the experimental results over the years by number of investigators in the area of polymeric based composites. Many research interests on the wear property of composites are conducted from academics and industries to enrich our knowledge's regarding physical, mechanical and tribological properties. The mechanical properties such as hardness, flexural strength and elastic modulus increased when the reinforcement contents in the matrix increased. In addition, it is evidenced that the micro-structures determine the mechanical and frictional properties of the composites.

This review carried out here indicates that key factors affecting the tribological behavior of epoxy based composites are the material factors such as fibers/fabrics/particles and matrix composition, fiber orientation, their sizes, distributions of carbon/ SiC/ Al_2O_3 particles in matrix, interfacial bonding between the reinforcement/matrix, and processing/operating factors like load, speed, distance and environment. Some mechanical and microstructural properties of the epoxy composite are introduced here. Furthermore, mechanism of increasing wear resistance and reducing friction coefficient for the polymeric composites are reviewed. Moreover, the prediction of tribological properties of the polymeric matrix reinforced with different types of reinforcements used for making the composites are overviewed using Taguchi and RSM techniques under abrasive sliding conditions. Finally, tribological applications of polymeric composites under various conditions are overviewed.

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