

## Review Article

# A Review on Tribological Behaviour of Polymeric Composites and Future Reinforcements

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Many different families of polymers are used in industries and engineering applications. The demands for studying the tribological behaviour of polymers and their composites are recently increased. This article briefs the most recent studies on the tribological behaviour of polymeric materials based on synthetic fibres. It reviews several factors which control the wear and frictional characteristics of such materials, that is, additives, fibres, interfacial adhesion, tribology environment, operating parameters, and composite geometry. In addition to that, new bioreinforcement (fibre) is introduced associated with preliminary results. The results showed that there is high potential of replacing the conventional reinforcement with the bioones.

## 1. Introduction

The simplest definition of a polymer is something made of many units since the basic unit is made of carbon, hydrogen, oxygen, and/or silicon. Polymers have been with us since the beginning of time such things as tar and shellac. They are processed with heat and pressure into useful articles like gears, bearings, bushes, and current engineering applications. All polymers materials are used in nearly every industry; natural and synthetic polymers can be produced with a wide range of stiffness, strength, heat resistance, crystallinity, density, and even price [1–4]. The volume of polymer consumed each year is already greater than that of steel [5]. According to ASTM D883 80c, polymers are divided into two groups with regard to their chemical and technological behaviour [1, 5]: thermosetting and thermoplastic. Figure 1 describes the polymer classifications and the possible reinforcements.

## 2. Thermoplastic

It becomes soft under heating condition and hard under cooling regardless of how many times the process is repeated

by heating and cooling conditions, thermoplastics can be rubber-like liquid, and in hard state it is glassy or partially crystalline. The properties of the thermoplastic polymers can be changed by changing length of individual chain, changing the form of the individual chains [1]. There are several major classics of thermoplastic material [6].

**2.1. Polyethylene (PE).** There are two types of PE, which are high-density polyethylene (HDPE) and low-density polyethylene (LDPE). LDPE is flexible and tough; HDPE is much stronger and stiffer than LDPE. It is used for sheeting, bags “squeeze” bottles, ballpoint pen tubing, and wires and cable insulation. HDPE is mainly used for piping, toys, household ware, and it is used as ultrathin film for the wrapping, in supermarkets and as the carrier bags.

UHMWPE (ultrahigh molecular weight polyethylene) is commonly used as an insert for one of the load bearing, articulating surfaces in orthopedic implants, such as the acetabular cup in the hip or tibial tray insert in the knee. This particular type of polyethylene is used because it has excellent biocompatibility and has a lower wear rate and coefficient

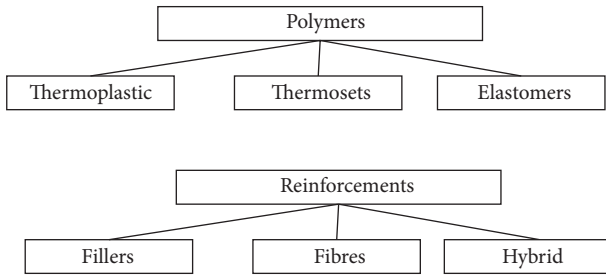


FIGURE 1: Classification and reinforcements of polymers.

of friction than other polymers. UHMWPE composites have a wide use in products. UHMWPE has been used in total joint replacement for the last three decades. Despite the recent advancements in prosthesis design, the wear of UHMWPE remains a serious problem [7]; controlling the quality of the polyethylene is essential to improve its wear resistance [7]. Some of studies have found that the tribological behaviour of the pure UHMWPE is lower than UHMWPE with composites [5–8]. UHMWPE and polypropylene (PP) were blended for enhancing the tribology behaviour of UHMWPE. By using sliding wear tests against steel ring, it is shown that antiwear properties of UHMWPE were improved notably by blending with appropriated content of polypropylene (PP) [8]. The coefficients of friction and wear rate of UHMWPE/PP blend were much lower than those of pure UHMWPE during sliding [8]. Kaolin and UHMWPE-based composite were prepared by means of polymerization filling and melt mixing, respectively. The study found that the kaolin filling greatly improves the tribology behaviour of UHMWPE. It is also found that the composites of UHMWPE with kaolin prepared by polymerization have much better tribological behaviour than the ones prepared by mixing with the same components and are promising self-lubricated material candidates for engineering application [9]. UHMWPE is induced by ion implantation aiming to increase the wear resistance of UHMWPE [10]. As a result, wear resistance of UHMWPE increases of about 76% after the ion implantation [10].

**2.2. Polypropylene (PP).** It is mainly used in its crystalline form for crates, containers, fans, car fascia panels, cabinets for radios and TV sets, toys, and chair shells.

Tribology behaviour of PP has been conducted in many researches [4–8]. Recently, it is found that the wear behaviour of PP is affected by the drawing ratio. The wear loss values dramatically increase with an increase in draw ratio when PP pin slides are normal to the drawing direction. These values of wear loss decrease to about 50% when the pin slides are parallel to the drawing direction. The use of grease lubricant reduces the wear loss to 10% of that achieved for dry motion [11]. Some developments have been carried out to increase the resistance of the PP against wear; mineral fillers are added to the PP for that purpose. The addition of mineral fillers to the polypropylene matrix decreases the wear resistance under severe abrasive conditions. Under mild abrasive conditions

the shape and size of the reinforcing filler influence the wear performance [12].

**2.3. Polyvinyl Chloride (PVC).** PVC is a linear-chain polymer with bulky chlorine side group; a range of plastics could be created with different additives to the PVC. It is a hard and rigid material, but the addition of the plasticiser can give it a flexible form. PVC is extruded to give sheet, film pipe, cable covering, and so forth. The rigid form (unplasticised) of PVC is used for piping for waste and soil drainage systems, rainwater pipes, and so forth. In addition, a copolymer is made by mixing PVC and vinyl acetate in a mass ratio of about 85% to 15% to give a rigid material, while a ration of 95% to 5% to give a flexible material. The rigid form of the copolymer is used for casing and covers, while flexible form of the copolymer is calendered to produce floor tiles. PVC is now the second most commonly used plastic material in terms of volume. Great achievements have been made in modifying its structure, behavior, and properties by including miscellaneous additives. Aspects of mechanical, thermal, and electrical properties of PVC composites were intensively studied in some researches [11, 12]. Wear of pure PVC has been tested [13] it shows that the additives (fillers) have different effects on the wear resistance of PVC composites according to the properties of the additives and the amount added. SiC and  $Al_2O_3$  as fillers improved the wear resistance of PVC significantly. Si and wollastonite also enhanced the wear resistance. Fly ash and  $B_4C$  reduced wear of PVC only when over 10% of fly ash or 7% of  $B_4C$  is added. Surprisingly, PVC filled with  $CaCO_3$  or  $SiO_2$ , the most commonly used fillers in industrial PVC materials, gave rise to a very low wear resistance [13]. PVC is in the flooring materials since the wear behaviour of flooring materials such as rubber, PVC (polyvinyl chloride), and cork was studied in detail [14].

**2.4. Ethylene-Vinyl Acetate Copolymer (EVA).** EVA copolymers are flexible, resilient, tough with good resistance to atmospheric degradation. The properties of EVA depend on the presence of the constituents since increasing vinyl acetate makes the copolymer more flexible. EVA is used for road-marker cones, ice-cube trays, medical and surgical ware, and as a major constituent in hot-melt adhesives.

**2.5. Polystyrene (PS).** PS has a lot of forms, generally; PS is brittle and transparent with a smooth surface finish material; toughened or high-impact PS is a blend of PS with rubber particles. It is used to make cups, vending machines, and casing. Expanded PS is a foamed polymer; it is a rigid form which is used for insulation and packaging. PS can be dissolved in petrol, dry cleaning agents, greases, oxidizing acids, and some oils. Exposure to detergents can cause stress cracking.

**2.6. Acrylnitrite Butadiene Styrene Terpolymer (ABS).** ABS is made by a combination of styrene-acrylonitrile copolymer (SAN), which is brittle in nature with polybutadiene; it makes ABS tougher. Upon the combination polybutadiene produces two forms: a graft terpolymer and a small rubber spheres

dispersed in the terpolymer and SAN matrix. ABS is an amorphous material. It is tough, stiff, and abrasion resistant; it is widely used as the casing boat shells and food containers.

**2.7. Polycarbonate (PC).** PC is below its glass transition at room temperature and so it is amorphous. PC is tough, stiff, strong, and transparent and retains properties well with increasing temperature. It has reasonable outdoor weathering resistance. Due to its tough properties, it is used where resistance to impact abuse and high temperatures encountered.

The static and kinetic contact of a PC against steel ball is experimentally examined to study its friction and wear behavior [15]. It is known that the wear takes place during the initial period; the steady stage is reached after sliding for 8 min, corresponding to the results of friction coefficient; and the wear volume shows a little increase due to the abrasion of the wear debris [15]. The utilization of block polycarbonate containing siloxane segments is well known to be of great interest for surface modifications [16]. The friction coefficient is strongly dependent not only on the surface enrichment of siloxane but also on the molecular weight of siloxane block segment. The initial friction coefficient has a little influence on the overall wear resistance due to the rapid wear process of the uppermost surface [16]. The reinforced polycarbonate resin Lexan 341R-739, containing 40% of weight of short glass fibres, is well known for their abrasive character [17].

**2.8. Acrylics.** Acrylics are mainly based on polymethyl methacrylate (PMMA), which has amorphous structure. They have stiff, strong material with outstanding weather resistance. Due to their transparency and weather resistance, they were used for light fittings, canopies, and lenses for car lights, signs, and nameplates. Opaque acrylic sheet is used for domestic baths, shower cabinets, basins, and lavatory cisterns.

**2.9. Polyamides (Nylons or PA).** PA is known as nylons, which has crystalline structure. There are a number of common PAs like nylon 6, nylon 6.6, nylon 6.10, and nylon 6.11. The two mostly used were nylon 6 and nylon 6.6 since nylon 6.10 has a higher melting point than the former and is also stronger and stiffer, and nylon 11 has a lower melting point and is more flexible. Nylons in general are strong, tough, and with high melting points. Glass spheres or fibers were added to give improved strength and stiffness. Molybdenum disulphide is an additive to nylon 6 to make it obtain low frictional properties. Nylons were used for the manufacture of fibers for clothing, gears, bearings, bushes, housings for domestic and power tools, electric plugs, and sockets.

PAs form a major class of tribopolymers used in almost all types of wear situations [18]. Abrasive wear studies on several types of PAs have been studied in a single pass condition by abrading a polymer pin against a waterproof silicon carbide (SiC) abrasive paper under various loads [18].  $\text{CH}_2/\text{CONH}$  ratio has a significant influence on various mechanical properties of elongation to break, fracture toughness, and fracture energy and, therefore, on the abrasive wear performance;  $\text{CH}_2/\text{CONH}$  ratio and various mechanical properties do

not show linear relation in most of the cases, while the specific wear rate as a function of some mechanical properties showed good correlation [18]. Currently, PA 11 and its three composites containing short glass fibres (GF) and metallic powdery fillers such as bronze and copper were investigated; GF reinforcement greatly improved the friction and wear performance of PA 11. Incorporation of bronze and copper powders in GF-reinforced composite further improves the friction and wears behaviour of PA 11. Copper proved to be beneficial filler than the bronze in this context [19]. The fundamental mechanisms of abrasion of 40  $\mu\text{m}$  diameter polyamide fibres have been reported [20] which shows that the abrasive process is responsible for a continuous diminution of the fibre cross-section until the creep failure stress is achieved locally [20]. The gear of a carbon fiber (CF) reinforced polyamide 12 (PA12) has been investigated in comparison with those of CF-reinforced polyamides such as polyamide 6 (PA6), polyamide 66 (PA66), and polyamide 46 (PA46). PA 12/CF gear has an excellent wear property under the condition that grease exists at the engagement region. PA12/CF gear indicated the highest load capability, excellent noiseless property, and the lowest water absorption among all polyamides investigated [21].

**2.9.1. Polyesters.** Polyesters have both thermoset and thermoplastic forms. The main thermoplastic form is polyethylene terephthalate (PET). It has similar properties to nylon; it is widely used in fiber form for the production of clothes. In industry, applications of glass-fibre-reinforced composite were increasing and plain polyester resin [22]. The wear behaviour of a glass-fibre-reinforced composite and plain polyester resin were experimentally investigated under several conditions and different parameters [22]. Short E-glass fibre-reinforced polyester composites with and without filler also were studied for the low stress abrasive wear behaviour in two and three body abrasions [23]. The abrasive wear of the composite depends on the entire test parameters like applied load, sliding speeds and abrasive particle size [22, 23]. The size of the abrasive particle and applied load tends to increase abrasive wear volume of the composites, whereas wear rate tends to decrease with increasing sliding velocity at constant applied load and particles of size ranging 200–300  $\mu\text{m}$ . Secondly, higher weight fraction of glass fibres in the composite improves the abrasive wear resistance because high energy is required to facilitate failure in glass fibres [23]. Polyester is used in making composite material, which is used for bearing applications [24]. Unidirectional reinforcements by linen and jute fibres were used, each in turn, in unsaturated polyester resin; the experimental results show the reinforcement volume fraction as well as orientation has considerable effect on the friction and wear of polyester composites [24]. An increase of fibre volume fraction to 33% increased the coefficient of friction of the tested material by about 14% and decreased its wear rate by about 95% at both low and high values of pressure velocity product (PV limit) when the fibres were oriented normal to the specimen surface [24]. The same increase in volume fraction of the fibres when oriented in the longitudinal and transverse directions

resulted in almost the same increase in the coefficient of friction (16%) while the wear rate decreased only by 65% at low PV value. For the same orientations at high PV value, the results showed no significant effect on the coefficient of friction while the wear rate decreased by 72% [24]. The proportion by weight of fiberglass used for the reinforcement of the polymer was conducted from 0 to 50% to investigate the tribology behaviour [25].

**2.9.2. Polyphenylene Oxide (PPO).** It is strong, rigid and has good dimensional stability. It can be mixed with polystyrene, which could be used for electrical fittings, dishwasher, and car fascia panels.

The influence of speed on the friction and wear of polyphenylene oxide (PPO) are determined and compared with polyetheretherketone (PEEK) and polytetrafluoroethylene (PTFE) in two sliding configurations under both dry and lubricated conditions [26]. With a line-contact geometry, the effects of debris aggregation on wear play a more important role than with a distributed contact. In lubricated conditions, with PPO in line-contact conditions, there is a "dwell period" in which lubrication persists following the removal of excess fluid from the contact, and this is shown to result from the formation of an aggregated layer of plasticized wear debris on the polymer surface [26].

The techniques of ion implantation were employed for improving surface hardness and wear resistance of polyphenylene oxide (PPO) [27]. The samples of PPO were implanted separately with Al, Ti, and Fe ions to three doses of  $2 \times 10^{15}$ ,  $1 \times 10^{16}$ , and  $1 \times 10^{17}$  ions/cm<sup>2</sup>. The result shows that wear resistance of PPO is improved significantly and friction coefficient is reduced. The  $1 \times 10^{16}$  ions/cm<sup>2</sup> Ti ion implantation produces the largest improvement in tribological properties, and wear resistance of  $1 \times 10^{16}$  ions/cm<sup>2</sup> Ti-implanted PPO improved over 270 times and friction coefficient is reduced by 40%. Nanohardness increased from 0.369 GPa for the plain PPO to 1.433 GPa for  $1 \times 10^{16}$  ions/cm<sup>2</sup> Ti-implanted PPO. TRIM96 (transport of ions in matter, version 1996) calculation revealed that ionization energy loss and energy loss difference between ionization and vacancies of Ti were more than those of Al and Fe beneath 50 nm ion implantation range, which were related to the largest improvement of surface properties for Ti ion implantation. IR spectra of  $1 \times 10^{16}$  ions/cm<sup>2</sup> Ti-implanted PPO indicated that the surface of samples is moisture-retentive and formed the carbonyl group [27].

The wear behaviour of a high temperature, composite plastic bearing material (polyphenylene sulphide, PTFE, lead oxide, and graphite in the ratio 55 : 25 : 10 : 10) were studied in journal bearing configuration against steel. The composition of the rubbing surfaces is studied using electron probe microanalysis (EPMA), and the physical properties of the composition at operating temperature were determined from shear modulus measurements. The results reveal a high lead content of is due to that rubbing involves the lamellar shearing of a lead oxide and possibly also a graphite layer which is aided by a relatively soft matrix containing PTFE [28].

**2.10. Polyacetals or Polyoxymethylene (POM).** One of the main forms is polyoxymethylene (POM), which is referred to sometimes as acetal homopolymer. In general polyacetals are strong, stiff, and have good impact resistance, low coefficients of friction and good abrasion resistance. Glass-filled acetal is used when higher stiffness is required.

Polyacetals are typical of thermoplastic polymers for sliding applications because of their frictional and wear characteristics [29]. Their wear mechanisms in composite and homogeneous form were investigated experimentally [29]. Subsurface deformation is found in all polyacetals tested. Crack nucleation at the matrix/glass fibre interfaces, crack propagation parallel to the surface, and cracks shearing to the surface were found in the composites. The results were consistent with previous results on nylons. Little is known about the first stages of this material transfer. Therefore, measurements was performed with polymers sliding onto steel were slightly investigated [30].

**2.10.1. PTFE.** Polytetrafluoroethylene (PTFE) is a linear polymer with high crystallinity. It is quite an expensive material. PTFE is tough and flexible and can be used over a wide range of temperatures, 250°C down to almost zero, and still retains its nature of being not attacked by any reagent or solvent. It is usually used where its special properties of low coefficient of friction is needed.

The tribological behavior of polytetrafluoroethylene (PTFE) and PTFE composites with filler materials such as carbon, graphite, E glass fibers, MoS<sub>2</sub>, and poly-p-phenylene terephthalamide (PPDT) fibers is studied [31]. The present filler additions found to increase hardness and wear resistance in all composites studied [31]. The highest wear resistance is found for composites containing (i) 18% carbon + 7% graphite, (ii) 20% glass fibers + 5% MoS<sub>2</sub>, and (iii) 10% PPDT fibers. Wear testing and SEM analysis show that three-body abrasion is probably the dominant mode of failure for PTFE + 18% carbon + 7% graphite composite, while fiber pull out and fragmentation caused failure of PTFE + 20% glass fiber + 5% MoS<sub>2</sub> composite. The composite with 10% PPDT fibers caused wear reduction due to the ability of the fibers to remain embedded in the matrix and preferentially support the load [31]. The results indicated that composites with higher heat absorption capacity exhibited improved wear resistance [31].

Adding glass fibres, the surface characteristics become better at least till 30%, but concentration of 30–40% produces wear as high as the polymer under the same testing conditions [32]. The friction and wear behavior of high performance polyimide (PI) and its composites reinforced with short cut carbon fiber and solid lubricants such as graphite, MoS<sub>2</sub>, and polytetrafluoroethylene (PTFE) are evaluated [33]. In order to gain greater insight into the relation between the wear rate, counterface surface topography, and the characteristics of the transfer layer formed of PTFE, a series of wear experiments were performed with a commercial POM – 20% PTFE composite sliding against hardened tool steel counterface [34]. The steady-state wear rate of the polymer is found to be influenced by both the surface topography of the steel



counterface and by the characteristics of the transfer layer formed after running in [34].

**2.11. Cellulosics.** The most common cellulosic materials are cellulose acetate (CA), cellulose acetate butyrate (CAB), and cellulose acetate propionate (CAP). CA is hard, stiff, and tough but has poor-dimensional stability due to its high absorption of water. CAB is tougher and more resistant to water uptake and hence more dimensionally stable. CAP is slightly harder, stiffer, and stronger. CA is widely used for spectacle frames, tool handles, keyboard keys, and toys. CAB is used for internally illuminated roadside signs, extruded piping, pens, and containers. CAP is used for toothbrush handles, pens, knobs, steering wheels, toys, and film for blister packing.

**2.12. Possible Tribological Behaviour of Thermoplastic and Fibre Thermoplastic Composites.** Summary of the tribological behaviour thermoplastic materials can be summarized and explained with the aid of Figure 2. In the case of the neat thermoplastic, the possibility of film transfer is very high. However, due to the fact that the sliding will take place between two polymers from the same type, high frictional force is expected in the interface which lead to high heat. The presence of the heat in the interface could deteriorate the soft surface when it exceeded the softening temperature ( $T_g$ ). The addition of the fillers and/or fibres will have two influences. Either it will reduce the heat in the interface by reducing the interaction between the asperities at which the film transfer will not be adhered well and detachments may occur. Another possibility is the strong film transfer made of polymer and debris of fibre may be formed on the metal surface. In this case, there are two possible surface properties which are either smooth surface or rough. In the case of the smooth surface, low friction and wear will be achieved. In the case of the rough surface, high wear rate may be obtained with high frictional force as well.

### 3. Thermosets

In general, thermosets are the materials which suffer of burning under high temperature. There is no melting phenomenon can occur on such polymer [5]. Thermosetting polymers are stronger and stiffer than thermoplastics and generally can be used at higher temperature. It is shaped directly from the raw polymer material, and no further processing is possible except machining which limits the possible processes to just moulding. Most of the moulding processes involve the addition of chemicals so that the cross-linked chains are produced while the material is in the mould. Thermosets have high thermal stability, high dimensional stability, high-stiffness, good resistance to creep, low densities, and high electrical and thermal insulating properties [1].

**3.1. Phenolics.** Its first synthetic polymer is phenol formaldehyde; it is supplied in the form of moulding powder, which includes resin, fillers, and other additional substance. The

filler is about 50 to 80% of the weight of the moulding powder. Applications for any composite material that has phenolic resin with paper or open weave fabric like glass fiber fabrics are gears, bearings, and electrical insulator parts.

**3.2. Amino Formaldehydes.** Amino formaldehydes include many materials such as urea formaldehydes and melamine formaldehyde. Both are highly cross-linked polymers; the widely used fillers are cellulose and wood flour. It has hard, and rigid, high-strength properties. Both are used for tableware such as cups, saucers, knobs, handles, light fittings and toys. Composites with open weave fabrics are used as building panels.

**3.3. Epoxides.** Epoxy resins become a thermosetting material if they are combined with a hardener since they are usually associated with glass or other fibers to give a hard and strong composite material. Epoxy resins have high adhesive strength, high hardness, chemical resistance; composites with glass fiber fabrics are used for boat hulls and tabletops.

A preliminary investigation into certain tribological aspects of filled epoxy-based plain-bearing composites was carried out [35] which shows that indiscriminate additions of irregularly shaped hard inorganic fillers may have a deleterious effect on the wear characteristics of the composite-metal pair. In addition there is evidence that minimization of the interactions between the epoxide matrix and the metallic counterface is necessary if a mild-wearing couple is to be realized [35]. The effect of counterpart material (hardened steel, austenitic steel, and  $Al_2O_3$ ), internal lubricant (PTFE, graphite,  $MoS_2$ , and  $SnS_2$ ), and fibre reinforcement (glass and carbon fibres) on the wear of epoxy-based composites has been investigated. Under dry conditions the high chromium austenitic steel led to a lower composite wear than the bearing steel, and only PTFE leads to a remarkable wear reduction. For wet conditions the  $Al_2O_3$  ceramic seems to be most promising. The carbon fibre reinforced version has the best wear performance under aqueous conditions [36]. The wear behavior of epoxy matrix composites filled with uniform sized submicron spherical silica particles is discussed [37]. The spherical silica particles could improve the wear resistance of the epoxy matrix even though the content of the fillers was at a relatively low level (0.5–4.0 wt.%). And it was found that the filler with smaller size seemed to be more effective in the improvement of the wear resistance of the composites [37].

**3.4. Polyurethane.** It is used to produce rigid foam. The advantage of using it over expanded polystyrene is that it has lower density, lower thermal conductivity, and better oil, grease, and heat resistance. The rigid foam can be formed in suit like in wall cavities for thermal insulation. Its applications were in refrigerators, structural sandwich panels in buildings, and marine buoyancy.

**3.5. Possible Tribological Behaviour of Thermoset and Fibre Thermoset Composites.** Summary of the tribological behaviour thermoset materials can be summarized and

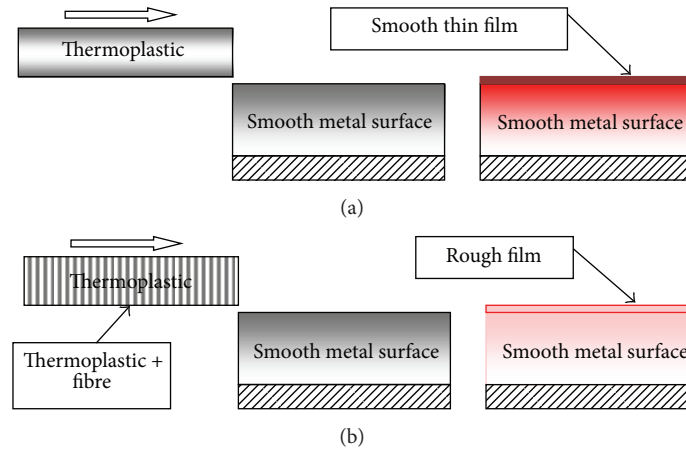


FIGURE 2: The possible film transfer when thermoplastics or fibre thermoplastic composites sliding condition on metal surface.

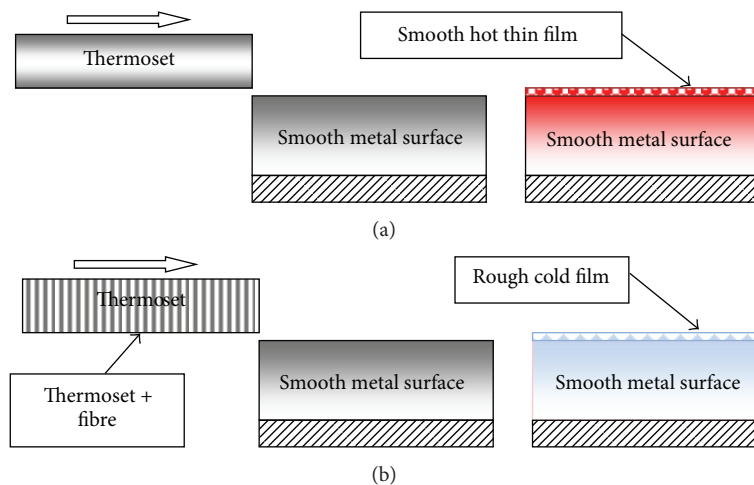


FIGURE 3: The possible film transfer when thermosets or fibre thermoplastic composites sliding condition on metal surface.

explained with the aid of Figure 3. In the case of the neat thermoset, the possibility of film transfer is lower than the thermoplastic since the thermoset is much harder than the thermoplastic. Another reason is the fact that the thermoset polymer has less plasticity than the thermoplastic. This leads to the conclusion that there is less possibility of plastic deformation, that is, forming the film on the counterface. However, most of the reported works mentioned that there is film transfer generated during the thermoset sliding against metal surfaces. In the case of the neat thermoset, it can be illustrated that the film transfer is rougher than the thermoplastic film, but the surface is cooler than the thermoplastic since the frictional force is less and there is possible of rolling debris in the interface. On the other hand, the thermoplastic has very high adhesive behaviour on the metal surface. In the case of the fibre/thermoset composites, the presence of the fibres will higher assist in cooling the interface and strengthen the exposed layer of the thermoset. However, in the case of fibre presence in the interface, the modification on the film transfer is high which could lead to

low friction due to the rolling of the debris and high wear due to the transition from adhesive to abrasive wear.

#### 4. Conclusion and Recommendations

There are several recommendations that can be withdrawn from this work as follows.

- (1) Thermoplastic materials have the ability of forming a thin film transfer on the metal counterface which assists in reducing the friction coefficient. However, at high level of interface temperature, plastic deformation occurs which deteriorate the soft surface leading to high damage. Reinforcing the thermoplastic materials will assist in reducing the wear rate of the materials which in turn can achieve good frictional and wear properties for bearings and bushes applications.
- (2) Despite the fact that thermoset materials are harder than the thermoplastic, the possibility of generating

the film transfer on the counterface is less and the property of this film is harder and can sustain high temperature. The addition of abrasive fibres to the thermosets could enhance the wear and the friction properties. However, the composites will suffer from instability condition during the serves. An attention should be put and comprehensive investigation need to be conducted in this area.

- (3) There are many polymers that have not yet studied in terms of tribology. Due to the importance of these properties which is equal to the mechanical properties, it is highly recommended for comprehensive study for such important materials.

The following can be concluded.

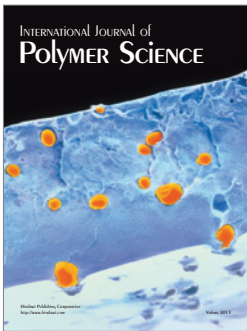
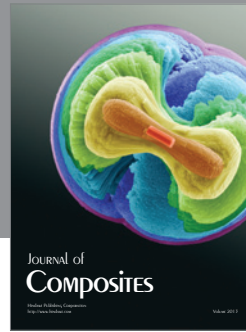
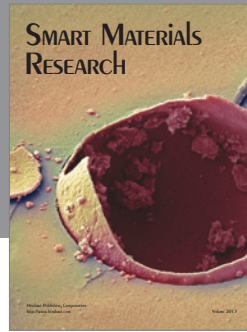
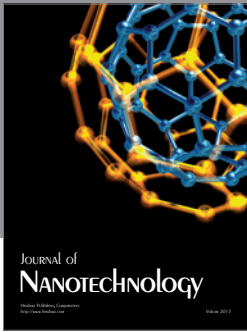
- (1) There is no general wear and/or frictional trend for either thermoset or thermoplastic under adhesive wear loading condition. However, most of the thermoplastic polymers generate a film transfer on the metal counterface which assists to enhance the wear and frictional performance of the materials. In the case of the thermosets, the modification occurred on the wear track that determines the wear and frictional performance of the materials. Therefore, it is highly recommended to study the wear track and its characteristics to comprehensively understand the wear behaviour of thermosets materials.
- (2) The addition of the fillers or fibres to either thermoset or thermoplastic materials assists in strengthening the surface which will result in enhancing the tribological behaviour of the polymer especially the thermoplastic. This is the general understanding for the adhesive wear loading conditions under dry contact conditions. Under wet contact condition, contradict thought was reported and further investigation is required.

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