




Scientific Insights on Tribological Aspects of Polymer Based Composites



Dheeraj Kumar Gara , G. Raghavendra , Shakuntala Ojha ,
Sri Bandyopadhyay, Syed Ismail, and R. Narasimha Rao

Abstract Polymer composites are those materials that form a synergistic mechanical advantage when reinforcement fillers are integrated into polymer. This advantage of the multiphase material possesses excellent wear and friction properties, hence found to be amenable with aerospace, automobile, and biomedical applications. The current article emphasizes the Tribological properties of various polymer composites concisely. However, alongside the Tribological advantage, there is a compromise in mechanical properties due to exposure of polymer composites to hazardous environments resulting in degradation and plasticization. With the advent of new manufacturing and processing techniques, by retaining the mechanical properties, the Tribological properties can be enhanced. In the current article, detailed attention to the microscopic and macroscopic Tribological aspects of polymer composites will be emphasized.

Keywords Tribology · Polymer composites · Characterization · Crystallography · Wear · Friction

1 Introduction

Realizing the friction (Gnecco and Meyer 2015; Mo et al. 2009) and wear (Bhushan et al. 1995; Gotsmann and Lantz 2008) at nanoscale provides interesting insights into the physical behavior of the material. Materials possess good wear resistance at a macro scale such as diamond can be used as a coating, but the same diamond-like

D. K. Gara · G. Raghavendra (✉) · S. Ismail · R. N. Rao

Department of Mechanical Engineering, National Institute of Technology Warangal, Warangal, Telangana 506004, India

e-mail: raghavendra.gujjala@nitw.ac.in

S. Ojha

Department of Mechanical Engineering, Kakatiya Institute of Technology and Science, Warangal, Telangana, India

S. Bandyopadhyay

School of Materials Science & Engineering, UNSW. Sydney, Kensington, NSW 2052, Australia

carbon structure is difficult to manufacture at nanoscale fidelity. Hence it can be inferred that it is more important to realize the design of materials at the nanoscale is more prominent than the macro level. The realization of understanding the wear mechanism atom by atom (Bennewitz and Dickinson 2008) per micrometer of sliding the surface and the critical length scale that controls the mechanism of wear (Bhushan and Kwak 2007) have provided substantial insight on the formation of wear debris between contacting asperities. However, It is evident from the literature that there are no adequate physical models available to predict the material loss due to wear (Aghababaei et al. 2016). It is intuitive to realize that friction and wear are the same but with different manifestations indicating they are not physical properties of the material but are responses to a system subjected to various loading environments. In this context, a distinction between the friction and wear must be revisited, wherein the friction is the resistant force developed between the two contact surfaces to initiate the micro-displacement of the sliding body and wear is the phenomenon of physical or chemical damage that influences the quality of material in contact.

2 Types of Wear

Thanks to the technology that most of the mechanical systems in the current industries such as aerospace, automotive, and biomedical have enabled the scientific community to understand wear at greater extinction due to their demand for new materials. Wear mechanism is classified depending on the type of loading environment and the type of response. For instance, consider there are two surfaces sliding over each other in the presence of strong adhesive forces, the asperities of one surface may fracture that results in debris and upon sliding will transfer this debris between the surfaces of the materials. This type of wear is referred to as adhesive wear whereas, if there is a loss of material due to relative motion resulting in damage of the actual surface is referred to as abrasive wear. In terms of area contact of polymer composites, the viscoelastic, viscoplastic, and relaxation phenomena are taken into account, whereas in the adhesion component of polymer composites, long-range Vander Waals forces play a crucial role. It is thus indicative that interfacial adhesion determines the bulk strength of a material within a solid. Theories such as Bowder and Tabor model, surface energy theory, and fracture mechanic model can determine adhesion components of friction such as interfacial shear strength and yield pressure of asperities.

In context to wear of polymer composites, an important observation is made by Wang (1999) suggesting that wear is cyclic in nature and begins with polymer matrix material (resin) at the initial stage. This phenomenon exposes the fiber to failure in either buckling or fracture where fibers are still supported by resin and if the fibers do not fail completely, they are observed as hairline burrs on materials and justified in Scanning Electron Microscopy (SEM). In order to discuss the wear at a wider perspective, the key events responsible for the material loss and generation of wear

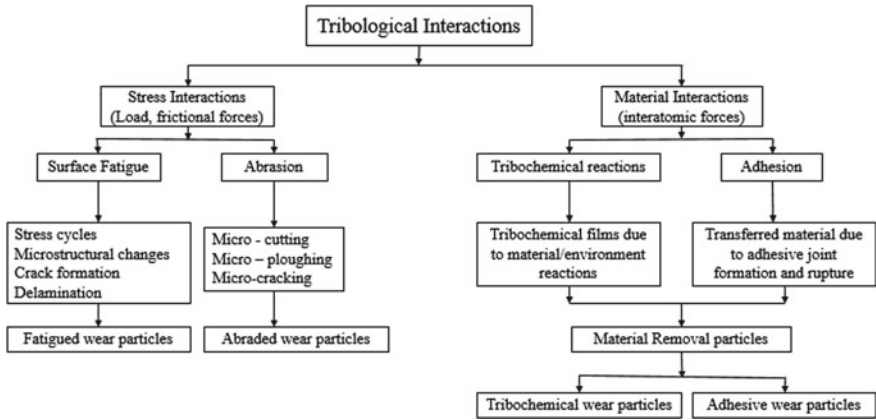


Fig. 1 Tribological interactions and wear mechanisms

particles from a given Tribological system are categorized into two broad classes as shown in Fig. 1.

The interactions and wear mechanisms displayed in the above Fig. 1 needs the attention of choosing a proper material that can alter the role of wear mechanism on the Tribological system. In lieu of this, to enhance the material Tribological properties, few polymer composites namely polymer/polymer and polymer/metal composites are predominantly elastic, as a result, the polymer tribology doesn't obey because the coefficient of friction varies according to normal load, sliding speed, temperature and glass transition temperature (Friedrich 2018; Omrani et al. 2016). To decide the reliability of the developed polymer composite, we calibrate the normal pressure- sliding velocity envelope as shown in Fig. 2.

It is implicative from various researches in the literature in pretext to above Fig. 2 that all material combinations exhibit a similar curve depicting coefficient of friction decreases linearly with the increase in applied pressure (Cirino et al. 1987). From the above discussion, it is intuitive to discuss the empirical relations between wear and

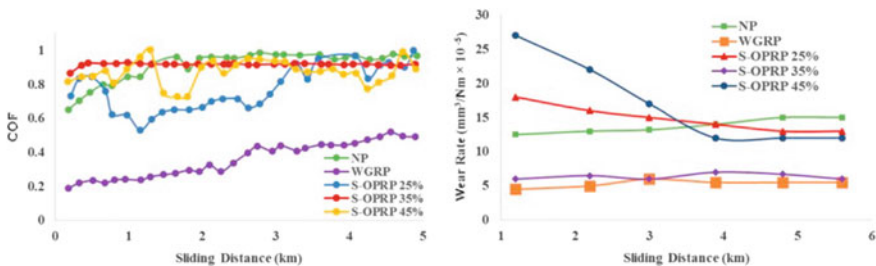


Fig. 2 Variation of friction coefficient and specific wear rate with sliding distance (Omrani et al. 2016)

other mechanical properties of polymer composites which will give a deeper insight into realizing structure–property correlation.

3 Mechanical Properties of the Polymer Composites

It is instinctive to discuss the mechanical properties of the polymer composites as they are sensitive to the microstructural variations that material undergoes. As it can be inferred that material wear which is purely a micro-phenomenon is implicative that the material mechanical properties get disturbed. Prior, it is important to emphasize the mechanical properties desired by the various industries such as biomedical, aerospace and automotive. In context to this, (Erenkov et al. 2010) emphasized the properties of polymer composites depend on electro-physical treatments, dipolymerization, cross-linking between the between matrix and filler. Key advantages of composites over conventional metals and alloys include high strength to weight ratio, excellent corrosion resistance and low thermal expansion. The major disadvantages include poor fire resistance and when exposed to high temperatures (typically higher than 400 °C), organic matrix will decompose and produce volatile and toxic gases. Composites most often creep, distort and soften which results in buckling and failure of load carrying capabilities. Properties of the polymer composites can be enhanced by the type of reinforcements, addition of nano-fillers. Few mechanical properties of natural fiber composites are discoursed in Ammar et al. (2018) as shown in Table 1 below.

These natural fiber reinforced composites depend on various parameters such as aspect ratio, volume fraction of fibers and fiber-matrix adhesion, orientation and stress transfer at the interface. Tensile strength is more sensitive to matrix properties and modulus is sensitive to fiber properties which can be inferred in Table 1. On the other hand, length of fiber, if exceeded than the critical length, upon the application of load increases the stress and results in higher strength of the composite. These properties are sensitive to microstructure and an emphasize between structure and property are correlated and will be discussed below.

Table 1 Mechanical properties of few natural fibers (Ammar et al. 2018)

| S.NO | Fiber | Specific gravity | Tensile strength (MPa) | Modulus (GPa) | Specific modulus |
|------|---------------|------------------|------------------------|---------------|------------------|
| 1 | Jute | 1.3 | 393 | 55 | 38 |
| 2 | Sisal | 1.3 | 510 | 28 | 22 |
| 3 | Flax | 1.5 | 344 | 27 | 50 |
| 4 | Sunhemp | 1.07 | 389 | 35 | 32 |
| 5 | Pineapple | 1.56 | 170 | 62 | 40 |
| 6 | Glass Fibre-E | 2.5 | 3400 | 72 | 28 |

4 Structure–Property Correlations

An imperative work by Lancaster (1968) in this framework established an empirical relationship between wear and other mechanical properties such as young's modulus, hardness, fracture strength, and strain to break. To derive the above parametric relations works from (Myshkin et al. 2005; Halliday 1955) have closely worked on a polymer/metal Tribological system and observed that the temperature of the metal at which wear rates increase rigorously is nearly equal to the softening points of the materials. This implies that there is sufficient time for the speeds of sliding to reach thermal equilibrium throughout the polymer to be affected by wear. This observation is motivated by the previous works from (Halliday 1955; Greenwood and Williamson 1966) suggested Hardness to Elastic modulus (H/E) ratio played a crucial role in determining the rate of wear. They have also measured the plasticity criteria for the asperity contacts involved (H/E) ratio. (Smithies 1952), in support of the above evidence, has evaluated the relation between instantaneous temperature and temperature constantly flowing from metal to polymer as Eq. 1.

$$T = T_0 \left(1 - \operatorname{erf} \frac{x}{2\sqrt{\alpha t}} \right) \quad (1)$$

where, T is instantaneous temperature in Kelvin, Metal surface at constant temperature T_0 , $\operatorname{erf} \frac{x}{2\sqrt{\alpha t}}$ is error function.

The difference between these temperatures decides the wear and surface roughness of the polymer. From the linear relation, it is conclusive that as the temperature difference arises, the surface roughness and wear increases. It is important that heating/cooling rates are often more important than the determination of temperature itself and hence Newton's law of cooling cannot be applied. This process is mostly referred to as wear scar measurements. We shall discuss the loss of mass of the material during the expansion of load which also increases the wear rate. Works pertaining to this statement can be justified in (Nuruzzaman et al. 2012; Ang and Ahmed 2013). The complexities involved in predicting the weight loss during the wear are that, at elevated temperatures, the wear scars show elastic recovery, and hence there is misleading in the measurement of wear rate. To surmount this complexity, the surface roughness of the metal can be increased so that wear per traversal can be increased. It may be noted that the temperature at which the rapid weight loss measured keenly signifying occurs at the softening point. The material loss is determined by the following relation

$$w_s = \frac{\Delta m}{\rho F_n L} \quad (2)$$

where, F_n is normal force (N), Δm is mass loss(Kg), ρ is density (Kg/m^3) and L is sliding length (m). Another important factor, surface roughness plays a significant

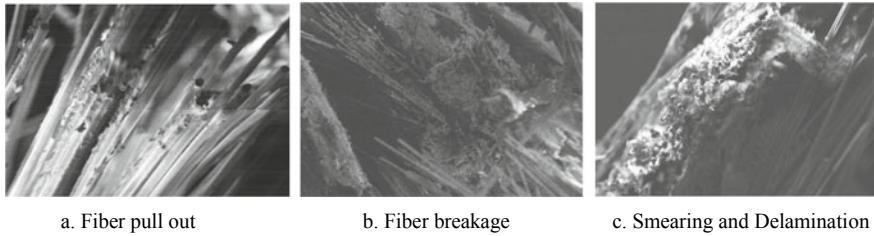


Fig. 3 Various surface failures of polymer composites

role in determining the magnitude of the wear rate. Impressive work by Kundalwal et al. (2014) analytically investigated the dependence of surface hardness of the polymer on the mechanical properties for the same. The paper demonstrated a shear lag model which concluded that when the surface roughness becomes larger, the tensile load transfer in the fiber/matrix interfaces also increases, this enhancing effect will gradually improve young's modulus of polymer composites. Interestingly, frictional shear transfer exists in thermoplastic composites and the interface is considered to be smooth if the ratio of amplitude to the wavelength of the matrix must be nearly zero, with few surface failures for reader understanding have been presented in the Fig. 3. The Fig. 3 discourses various surface failures and respective fiber failures at microstructure scale. Fiber pullout is one of the failure mechanisms that occurs due to weak bonding as it can be seen in the SEM image (first left). Fiber breakage is accompanied by interface debonding, this is because of the higher stress placed on fiber resulting in early fatigue. This is observed in the SEM image in the Fig. 3 (second left). Whereas influence of layup configuration and feed rate plays a crucial role resulting in matrix smearing and this can be reduced with a proper adhesive bonding, a SEM image shown in complete right of the Fig. 3 followed by delamination failure which is a most common failure observed in the polymer composites, this is generally developed because of the excessive out-of-plane and interlaminar stresses, the SEM image clearly shows the delamination concisely as shown in complete right image in Fig. 4. Similarly for the elastic transfer for thermosetting polymers. In the preprocessing discussion of surface roughness, processing techniques define the surface properties of any polymer. In lieu of machining context, (Jaśkiewicz 2019) indicated the surface roughness enhanced with an increase in cutting speed whereas decreased with increasing feed rate. An extension of Lanz et al. (2001), the authors have also conferred that the machining direction of milling has also played a significant role.

Due to the advent of technologies, various materials have been developed by the researchers in the scientific community that can be cited in the literature. Polymer composites received ample attention from the aviation industry due to their intriguing properties such as high strength to weight ratio, good thermal and corrosion resistance. Hence the development of polymer composites from various materials such as in combinations of natural fibers and metals has foreseen tremendous effort by researchers. As a result, erosive wear has received ample attention, in lieu of this,

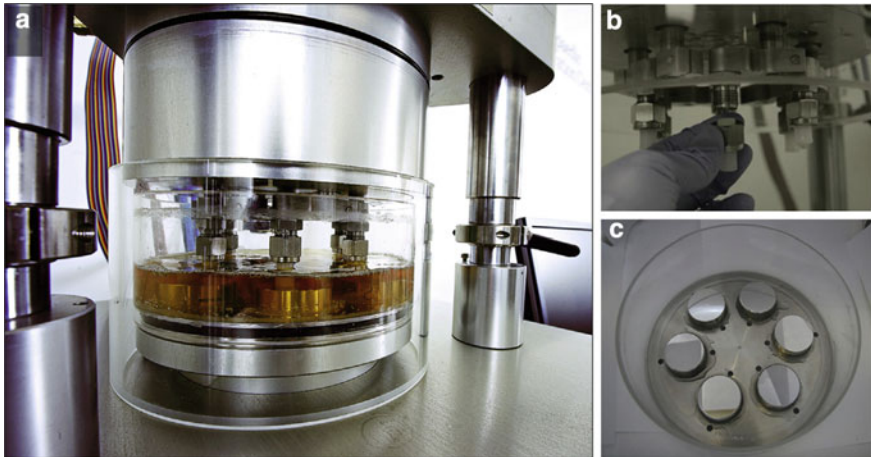


Fig. 4 Typical POD wear tester. **a** Assembled POD wear tester, **b** UHMWPE pins secured in the holder, **c** CoCr disks secured in the test chamber (Zdero et al. 2017)

(Tewari et al. 2003) has earmarked with erosive studies of polypropylene composites reinforced with glass fibers at different sand impact angle (30, 60 and 90) and concluded that erosion wear of the polymer composites depends on the orientation angle mostly between the range of 45–60. An idea on how wear behaves and its effect on material properties have discoursed sufficiently. An intuition to understand the behavior of wear from testing is always challenging as they are not tested under a similar environment and hence there might be a scatter in the data due to environmental exposures. Therefore we shall discuss the standard testing procedures followed for the wear test in the following session.

5 Wear Test and Characterization

The difficulty of replacement, repair, and maintenance of industrial tools and equipment has become so tedious and hence there is a decline in production due to wear. In more detail, erosion wear is one of the categories of wear mostly observed in industrial applications. As a result, standard wear testing procedures have developed. However, there is inadequate work pertaining to the erosive wear behavior of the polymer composites. This is due to the composite characteristics such as particle size, fiber content, impingement angle, impact velocity, and temperature. Works from (Harsha et al. 2003; Tewari et al. 2002) have experimentally confirmed that natural fiber polymer composites semi-brittle behaviors when tested for an erosion wear behavior. This is because of the non-uniform distribution of the filler in the polymer matrix which induces large voids yielding severe premature cracks. This measurement is very crucial in determining the strength of the composite material

that enables scientists to establish a proper structure–property correlation. Next to that, the experimental conditions such as impact angle, erodent shape, and angle and erodent flux rate, etc. have a crucial role in altering the wear behavior of the composites. Since the matrix is removed first, the erosion characteristics of resin materials are the prime factor for the resistance of composites.

Pin on the Disk wear test is the standard test procedure followed by the scientific community to evaluate the wear behavior of polymer composites. Setup pertaining to PoD can be seen in Fig. 4 as shown below which is retrieved from Zdero et al. (2017). More detailed information can be retrieved from the citation. The procedure followed by the PoD wear test is categorized in stages as.

1. Methodology
2. Materials and tool list
3. Specimen preparation
4. Specimen testing
5. Raw data collection
6. Raw data analysis
7. Results.

The results contain weight loss and average surface roughness, gravimetric wear rate (steady-state wear rate) followed by illustrative wear patterns.

The most interactive and powerful experimental techniques such as scanning electron microscopy (SEM) and atomic force microscopy (AFM) which provide deeper insights into the microstructure on which physical properties of the polymer composites depend. The important observations that are needed to be observed during the microstructural evolution of polymer composite behavior include changes to individual macromolecular segments (on a nanometer scale), localized plastic yielding in the form of crazing or shear bands (at the micrometer scale), up to crack propagation and macroscopic fracture (at the millimeter scale) as shown in Fig. 5.

The easiest way is to study composite materials is to produce a brittle-fracture surface as it can give a clear picture by eliminating the plastic deformation that

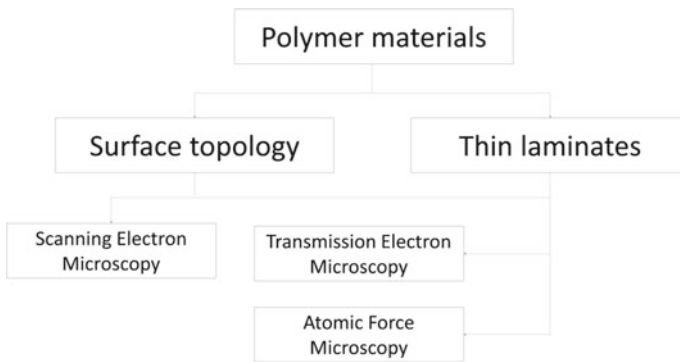


Fig. 5 Microscopy process of polymer composites

hides surface morphology. This is achieved at low temperatures (equivalent to liquid nitrogen). But still, there are complexities to locate the hard filler particles in a matrix visible, to overcome this complexity, soft matrix fracture, a fracture phenomenon at elevated temperatures enables hard filler particles visible. Evidence to this context, (Srivastava et al. 2020) calibrated the visibility of inorganic filler particles in a PP matrix on fracture surface using SEM for Acrylonitrile butadiene styrene (ABS) thermoplastic polymer composite which can be visualized in Fig. 6.

To enhance the contrast of the structure, there are various techniques but the simultaneous evaporation of platinum/carbon film has proven to be the best. SEM investigations have the advantage of revealing morphology and micromechanical properties that enable researchers to establish structure–property relations at ease. A figure to overview this understanding is given in below Fig. 7 that emphasizes the micromechanical processes in polymers (Greenhalgh 2009).

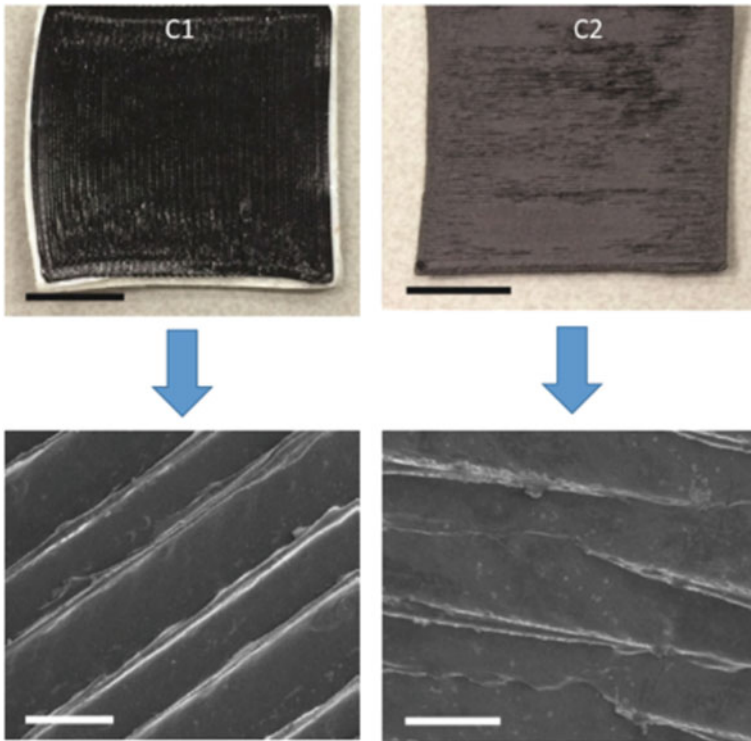


Fig. 6 SEM 3D-printed monolayer of polybutylene terephthalate (PBT)/CNT composite (C1) and PBT/graphene composite (C2) with their SEM images (Srivastava et al. 2020)

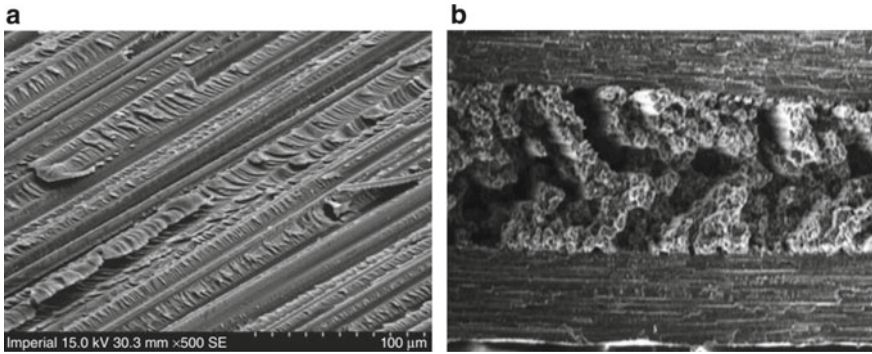


Fig. 7 Micromechanical processes in polymers **a** Fracture surface for high tilt (55°) **b** cross ply laminate failed in tension (Greenhalgh 2009)

6 Structural Hierarchy and Enhancement of Wear Resistance of Polymers

Classification of polymeric materials shows a wide variety of molecular hierarchy such as structures ranging from 0.1 nm to 1 mm orders of magnitude. It includes molecular level 0.1 nm, microscopic 10 nm, mesoscopic level 1000 nm, and macroscopic level > 0.1 mm scale. In realizing the relationship between the micro and macroscopic mechanical properties, the constitution influences polymerization, configuration, and conformation influences processing temperatures and free volume influences yield stresses of the polymers. With an increase in the molecular weight, the strength of the polymer increases with a sharp increase at critical molecular weight, this is because of the rest molecules that help to form entanglements in the amorphous interlamellar regions and the defects therein (Michler 2008). In conjunction with this statement, the following Fig. 8 refers to the defects and entanglements of the polymer.

For the polymer composites, the presence of fewer weak entanglements of polymer chains suggests that the polymer has better strength. Whereas the toughening of the polymer composites depends on interfacial strength, void formation, and deformability of interparticle matrix strands which in detail is discussed in Lednicky and Michler (1990).

Enhancement of wear resistance of the polymer composites has received ample attention in the materials community due to their intriguing properties such as high strength to weight ratio, corrosion resistance, and thermal resistance, as a result, a compromise in the wear of the composites have been constrained the limitations for the applications. To surmount this hierarchy, nanocomposites have been introduced extensively to the material group which enhanced the Tribological properties of polymer composites to a greater extent. We shall in the current context discuss few works from the literature and work carried out by the composites group from the authors' experience. The synergism required to add Nano fillers into polymers has

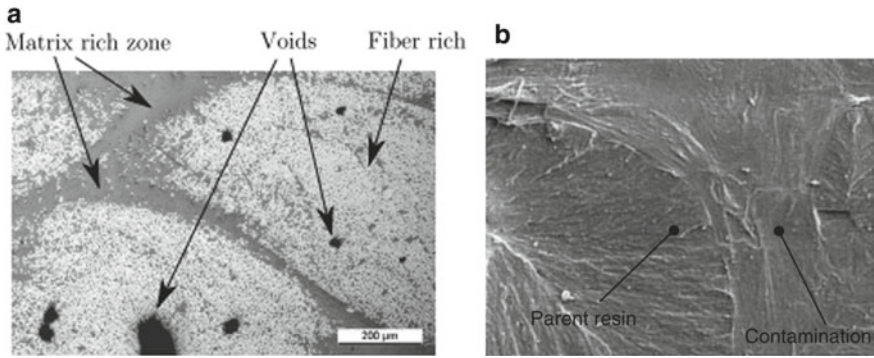


Fig. 8 a Defects (Vajari et al. 2014) and b entanglements of the polymer composite (Greenhalgh 2009)

to satisfy the size of the nanoparticle filler, the number of filler particles, and the interfacial area. These three natures can be visualized in the following Fig. 9 as follows (Michler 1999; Robertson 1976; Fukushima and Inagaki 1987; Giannelis 1996).

Based on the filler particle dimensions, nanocomposites are classified as Zero dimensional fillers, one-dimensional fillers, two-dimensional fillers, and three-dimensional fillers. An excellent review of the intrusion of filler particles into polymers has been cited in Friedrich et al. (2005) is listed below in Table 2 along with the respective micrograph as shown in Fig. 10

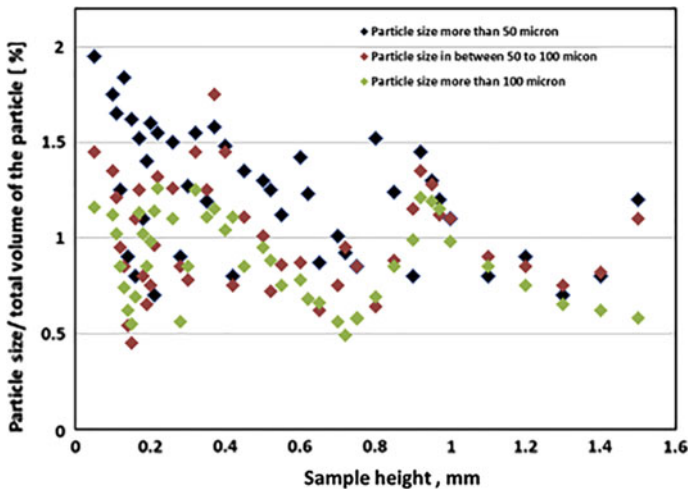


Fig. 9 Nature of filler particles and their percentage of intrusion as a function of shape and size/volume (Samal 2020)

Table 2 Various fillers for polymer composites and their wear behavior (Friedrich et al. 2005)

| Material composition (Vol%) | | | | | | | Specific wear rate (10^{-6} mm/Nm) |
|-----------------------------|------|------|----------|------|--------|--------------------------------|---------------------------------------|
| PTFE | PPS | PEEK | Graphite | CF | Bronze | Al ₂ O ₃ | |
| 51.6 | 31.8 | — | 4.8 | 11.8 | — | — | 1.53 |
| 51 | 31.6 | — | 3.9 | 13.5 | — | — | 1.40 |
| 51.9 | 32.4 | — | 2.6 | 13.1 | — | — | 1.20 |
| 12.4 | — | 61.8 | 11.7 | 14.1 | — | — | 4.31 |
| 9.7 | — | 49.7 | 12.5 | 28.1 | — | — | 6.33 |
| 76.8 | — | — | 19.8 | — | — | 3.4 | 22.40 |
| 84.1 | — | — | — | 12.6 | — | 3.3 | 1.25 |
| 52.5 | 28 | — | — | 19.5 | — | — | 1.69 |
| 78.6 | — | — | — | 21.4 | — | — | 1.75 |
| 80 | — | — | — | 10 | 10 | — | 0.565 |

Block-on-Test-ring tests. Testing conditions $p = 2$ Mpa; $\vartheta = 1$ m/s; $T = Rt$; $t = 8$ h; counterpart: steel

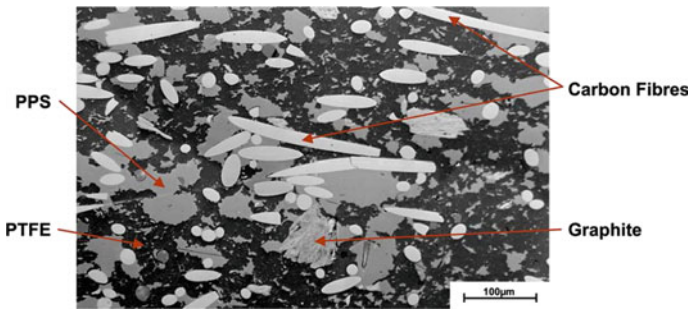


Fig. 10 Micrographs of various filler particles (Friedrich et al. 2005)

7 Case Study

An extensive Work from Prakash et al. (2020) on investigation of Tribological properties of porous nano activated carbon has been discoursed. The paper credits the enhancement of wear resistance of composites by 106% by inclusion of 1% of nano-carbon and more importantly irrespective of percentage of carbon content (1–3%), composites exhibited semi ductile erosion wear behavior. These composites were tested for solid particle wear on the sand erosion test rig as per ASTM G76 standards with 200 µm size of silica as erodent. After finishing the test, the samples were cleaned with acetone and are weighed to near accuracy of 0.001 mg. The author concluded with previous investigations that due to proper arrangement of filler particles, the wear resistance has shown substantial improvement which can be attributed to impressive mechanical properties as shown in Fig. 11.

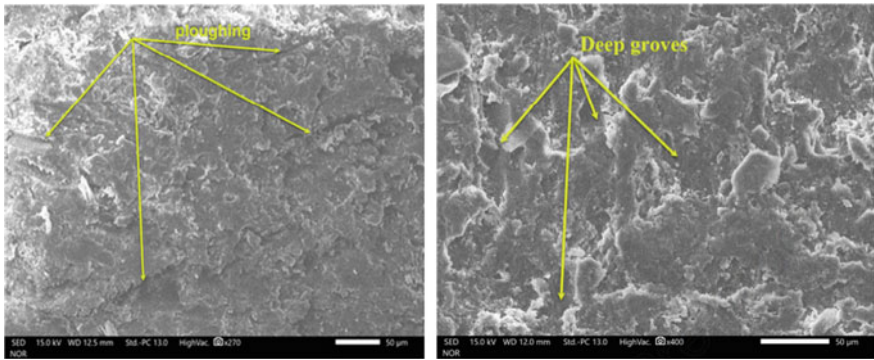


Fig. 11 SEM Micrographs of ploughing and deep groves for 2 wt% porous activated nano carbon (Prakash et al. 2020)

From the SEM observations, further increase in the carbon content will decrease the wear resistance and this is attributed to poor interfacial bonding and wettability. Thus as discussed earlier, it is important to realize proper content of filler that a polymer can accommodate to enhance the properties of the composite. The paper also credits the impact of load on the wear rate, after a suitable load (for an instance in the current work 20 N) led to increase in wear rate, and upon increasing the abrasive particles deeply penetrate in the material causing removal of material. These worn surfaces have deep groves just as shown in Fig. 12 above and respective detached filler particles in Fig. 12 below.

Another work from Ojha et al. (2014) have investigated wear behavior of carbon filled polymer composites and found that carbon black particulates showed excellent wear as compared to raw particulate composite and semi-ductile failure as discussed earlier in the beginning of the chapter have been reported indicating the enhancement

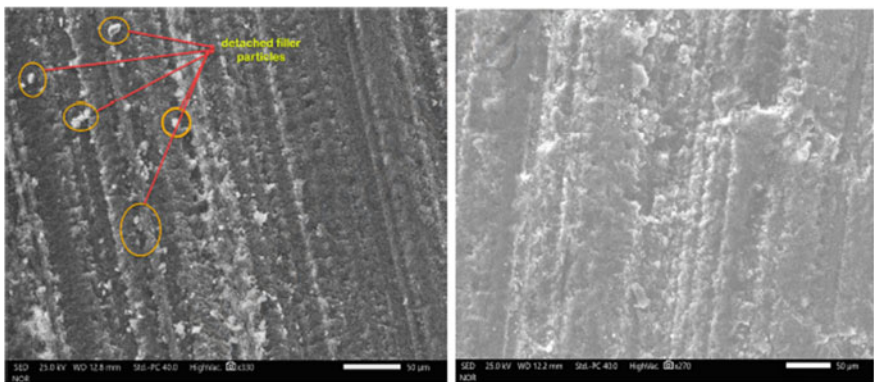


Fig. 12 SEM Micrographs for 2% carbon reinforced composite (particle detachment-left), ploughing (right) (Prakash et al. 2020)

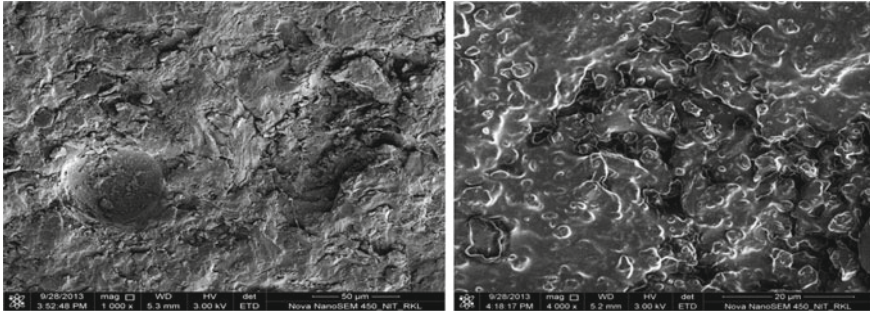


Fig. 13 SEM Micrograph for carbon black filler polymer composite (right) and raw composite (left) (Ojha et al. 2014)

of mechanical properties. It is conferred that with 10 wt% filler composite has shown good interfacial bonding between fibre and composite material whereas after adding 20 wt% of carbon black particulates the surface has become hard compared to raw composite due to increase of carbon composites as shown in Fig. 13.

8 Conclusions and Future Scope

Polymer composites show excellent mechanical properties when compared to the Tribological wear properties. But their provision to enhancement of these properties has processing advantage. Hence a wide range of opportunities in terms of filler materials can be added at a suitable percentage to the polymer chain that can accommodate the third party filler particles into the matrix that can exhibit excellent wear resistance alongside improving the other mechanical properties. These materials poses excellent wear materials has huge potential for the aviation, automobile and biomedical industries. A foresee to improve more advanced materials where wear is expected to have inherently the best that can simply be altered by just processing parameters. These materials sometimes referred to be as Functionally Graded Materials (FGMs) and smart materials.

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