A Critical Review on Hybrid Polymer Composites: In the Context of Reinforcement and Wear

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***Abstract*- Hybrid polymer composites' (HPCs) wear and physio-mechanical characteristics are the main problems facing technical applications. This manuscript attempts to provide an overview of the studies conducted by different investigators on fiber, particulate reinforced polymer composites, industrial wastes and their use in polymer composites, abrasion and erosion wear, and systematic experiment design. Compared to two body research, it has been discovered that fewer investigations have been done to examine the three-body abrasive wear behavior of ceramic-filled HPCs. Even though the impact of fillers relative to matrix change is more significant, there has been very little research on the effect of particle fillers on the erosion properties of hybrid composites.**

***Keyword* - Wear, Industrial Waste, Fiber Reinforcement, Particulate Filler, Polymer Composite.**

1. Introduction

With more industrial and technological applications than monolithic metal alloys, hybrid polymer composites, or HPCs, are a superior tribo-engineering material that are widely used. This is primarily because of their many inherent advantages, which include better strength-to-weight ratios, effective stiffness-to-weight ratios, and higher wear resistance. Its higher cost and unpredictable qualities have limited its usage despite these benefits.

Enhancing qualities through the application of inexpensive, widely accessible fillers is a practical and cost-effective solution. Fillers are added to components for two reasons: first, they improve the component's mechanical and tribological qualities; second, they increase the component's economy. Thus, the right choice of fibers, fillers, matrices, and processing methods makes it possible to create materials that are specifically tailored to match the needs of

2. Polymer Composites with Particulate and / or Fiber Reinforcement

A proper blend of fibers and matrix can be chosen to create a composite with high strength and modulus. Fiber-Reinforced Polymer Composites (FRPCs) have better mechanical properties in the plane direction because fiber, which is stronger than the polymer matrix, bears the load in the fiber direction. However, the fiber/matrix interface and the interphase adhesive bond in the out-of-plane directions—which are often on the lower side—also affect mechanical properties. This is explained by the matrix's tendency to shatter at lower strains and its incapacity to transmit stresses to the fiber. Interface strength and matrix toughness have increased as a result of numerous attempts to improve mechanical qualities by altering the epoxy matrix. Solid fillers are one method of enhancing the composite's physiomechanical characteristics. Occasionally, certain fillers are included into the matrix to improve the properties of the composites.

Studies have indicated that inserting filler particles into a fiber-reinforced matrix can produce synergistic benefits in hybrid composites [2, 3]. The results of this investigation demonstrated how adding filler particles and/or fiber reinforcement can have synergistic effects.

2.1. Particulate filled polymer composites

Due to a number of benefits, including cost-effective production, altered electrical and magnetic properties, better processing, flame-retardancy, complex shape formation, wear resistance, isotropic nature, density control, thermal conductivity, toughness, etc., particulate-filled polymer composites have emerged as one of the most widely used engineering materials. Furthermore, taking into account the thermal expansion of the matrix and reinforcement, they are less thermally sensitive than long fiber composites [4, 5].

Hard particulate fillers, such as glass fiber (GF) and metal or ceramic particles, have been shown to significantly increase the performance of polymer composites. Numerous industrial uses for metal particle reinforced polymers exist, including extremely thermostable materials, heaters, electrodes, and more. In the past 20 years, numerous researchers have conducted substantial study on ceramic-filled polymer composites. The impact of the shape of the silica particle on the mechanical properties of polymer composites was brought to light by Yamamoto et al. [14].

Nakamura et al. [15–16] provided evidence for this by concentrating on how the size and shape of silica particles affect the toughness and strength of composites by utilizing the adhesion property between the particle and matrix. The strength of the composite as a whole is often determined by the stress transfer between the matrix and the particle [17]. Nevertheless, in the case of loosely linked particles, this interaction is exactly the opposite, and the strength of the composite was reduced.

The majority of earlier research was based on [18], which examined the thermoplastic composites' tensile characteristics, which were mostly influenced by the form of the particles.

Nevertheless, Patnaik et al.'s study [19] discovered that additionally.

2.2. Fiber-Reinforced Polymer (FRP) Composites

Fibers and a polymer matrix play different functions in FRPCs. The matrix serves as a supportive agent and shields the fiber from environmental harm, while the fibers give the composite a higher modulus and strength. Types of fiber that are frequently utilized are (a). Synthetic fibers such as carbon, aramid, silica/glass, and (b) Natural fibers such as jute, sisal, etc. Flexible polymer composites (FRPs) have been widely used in a variety of industries, including aviation, transportation, offshore structures, electrical appliances, and fatigue strength. These applications stem from FRPs' remarkable flexibility, light weight, wear resistance, impact resistance, and fatigue strength.

An extensive report on the physio-mechanical properties of PVC composites was provided by Khalil et al. [31]. The study concentrated on the composites' characteristics while accounting for a variety of impacts, such as plasticization.

3. Industrial Wastes and its Application in Polymer Composites

The use of industrial wastes as fillers in composite preparation, such as fly ash, red mud, etc., has not received much attention in research. However, using flyash or other industrial wastes can be more economical than using more expensive conventional fillers like silica or ceramic. Furthermore, disposing of garbage is less expensive and easier. Vaisanen et al. [56] reviewed the literature that was accessible on the implications of organic waste as matrix modification or reinforcement in polymer composites, excluding implications of organic waste and residues as low-value energy sources, land-filling, composting, or anaerobic digestion. Experimental variations in the tensile strength and stiffness of composites, as well as the weight percentage of iron-ore-tailing in epoxy and polypropylene, were reported by Onitiri and Akinlabi [57]. They also contrasted outcomes from theoretical models. It was discovered that adding iron ore tailings improved the composites' rigidity.

The impact of HPCs with jute/granite powder reinforcement in an epoxy matrix was investigated by Pawar et al. [58], who found improved tensile and flexural capabilities. When compared to a 10 weight percent loading, the jute epoxy composite with a 24 weight percent loading of granite powder showed a 25% increase in impact strength and a 51% increase in hardness. In addition, the fracture toughness of the composite was improved by 10 to 50 weight percent fiber loading.

Utilizing mining waste was highlighted by Pani et al. [59–62] (Overburden and top . The red mud produced by the Bayer process, which is used to recover aluminum, is another often used industrial waste. Red mud has a wide range of uses in construction before it is used in composites, including the creation of tiles and bricks [75]. Red mud can be used to make aluminum titanatemullite composite, according to a study by Mahata et al. [76]. These fundamentals served as the foundation for the research done by Zhang et al. [77] and Akinci et al. [78] to assess the thermo-mechanical characteristics of red mud/PP composites. Red mud/GF/epoxy hybrid composites were created and examined by Biswas et al. [79], who also reported on the composites' mechanical characteristics and erosive wear behavior. Bhat et al. [80] conducted a second research to investigate the financial viability of employing.

4. Wear in Polymer Composites

Tribology is the study of the interaction between two moving surfaces. Wear and material loss are caused by the relative motion of two surfaces. Furthermore, external environment-induced mechanical (fracture or deformation) or chemical (oxidation) stimuli can also contribute to the wear process. A material's surface topology may alter during the wearing process as a result of substance loss or surface erosion brought on by the hardness of solid particles or the continuous motion of liquid droplets. All sectors in the world consider the phenomena of wear to be expensive since it results in significant financial losses. For this reason, developed countries started conducting methodical study to analyze the wear process and its consequences. The main drawbacks of wear include increased expenses, the need to replace worn-out components more frequently, longer manufacturing times, decreased productivity, and energy loss. It may also lead to catastrophic failures that occasionally result in the loss of human life.

One type of tribo-engineering material is FRPCs, or multi-constituent composites, due to its excellent wear resistance, high specific strength, and modulus.

characteristics [91]. It has numerous uses in a variety of industries, including roads, trains, electrical equipment, general mechanical components, structures, and public works.

4.1. Abrasive wear

Relative motion between two surfaces that are forced against one another causes abrasive wear. Groove marks are produced when material from the softer surface is removed by the hard asperities at the interface [93]. It is possible for this continuous sliding to cause plastic deformation, fracture, or groove creation depending on the kinds of materials and their characteristics. It happens when materials are concurrently removed by microploughing and microcutting. Coal handling equipment in power plants, gear pumps that handle industrial fluids, mining and earthmoving equipment, crusher walls, ball mill liners, and balls, among other things, all exhibit this type of wear.

4.1.1. **Mechanism of Abrasive Wear:**

4.1.2. The synchronous, simultaneous, and separate micro-ploughing, micro-cutting, micro-fatigue, and microcracking functions comprise the abrasive wear mechanism. When a particle with an abrasive tip contacts a surface at a large attack angle during micro-cutting, abrasive wear takes place, resulting in the formation of a surface groove, as seen in Figure 1(a). The displacement of material from the impact or groove location with material loss is depicted in Figure 1(b) [95]. Microcracking or micro-fracture is seen in brittle particles. A comprehensive explanation of the micro-cracking mechanism is shown in Figure 1(c). As seen in Figure 1(d), wearing results from micro-fatigue, which is the process of a blunt end particle causing abrasion on the ductile material by constant loading and unloading.

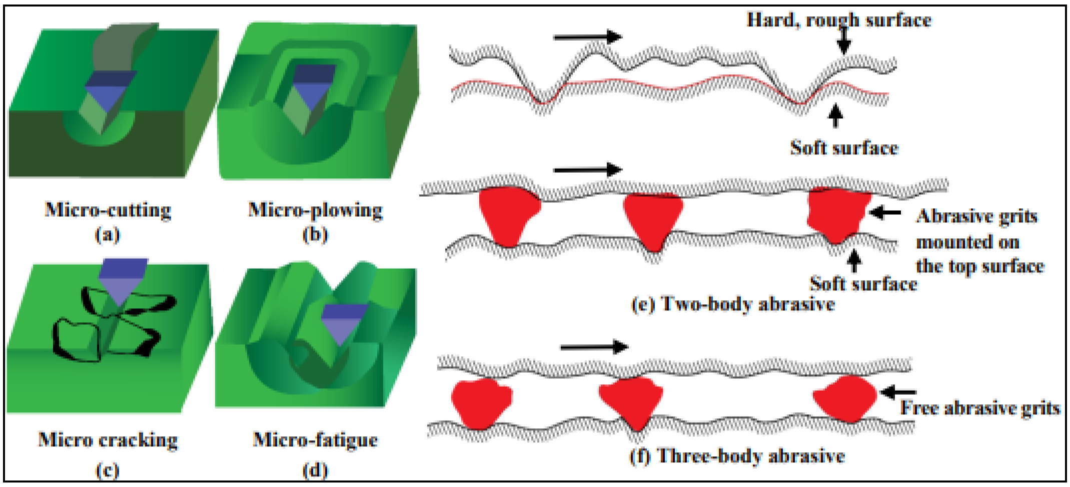


Figure 1. Schematic illustrations of abrasion wear mechanism [96, 97]

Abrasion wear is classified into two categories, i.e. two-body (bound abrasive particles) and three-body (free to slide) abrasion. When two bodies—one of which is harder—are in motion when cutting, grinding, or machining, this is known as two-body abrasion. Figure 1(e) depicts damage from twobody abrasions. As seen in Figure 1(f), three-body abrasion wear happens when a hard particle serves as an interface third body between two moving bodies. Industrial and agricultural equipment, such as gear pumps handling industrial fluids, coal handling equipment in power plants, mining and earthmoving equipment, ball mill liners, crusher walls, and balls, are heavily affected by these wear issues. A survey of the literature indicates that, in comparison to two-body abrasion wear difficulties, three-body problems are less researched and examined, and there don't seem to be as many publications on the impact of different fiber/filler reinforcing.

4.1.3. **Abrasive Wear Characteristics of Polymer Composites:** About 50% of all wear difficulties and almost 60% of the total cost are attributed to abrasive wear [97, 101]. Industrial and agricultural equipment exhibits threebody abrasion, while material removal processes show twobody markings [102]. Abrasion causes for about 90% of wear, while fatigue accounts for 8% [103]. As was previously said, in the event of an abrasion, the two hard surfaces glide against one another [104]. The abrasive wear behavior of polymer composites has attracted the attention of numerous researchers. The abrasion wear performance of hybrid composites made of epoxy and modified coir fiber was manufactured and examined by Khan et al. [105]. Using pin-on-disc wear testing apparatus, two parameters—sliding velocity and normal load—were examined in order to show the behavior of abrasion resistance. Acharya and Mishra [106] . Abrasive wear is responsible for around half of all wear issues and over 60% of the overall expense [97, 101]. Threebody abrasion is seen in industrial and agricultural equipment, whereas twobody markings are shown in material removal processes [102]. About 90% of wear is caused by abrasion, and the remaining 8% is caused by fatigue [103].

As mentioned before, the two hard surfaces slide against each other in the event of an abrasion [104]. Many researchers are interested in polymer composites because of their abrasive wear behavior. Khan et al. [105] produced and evaluated the abrasion wear performance of hybrid composites consisting of epoxy and modified coir fiber. Two factors were analyzed to demonstrate the behavior of abrasion resistance: sliding velocity and normal load, using pin-on-disc wear testing apparatus.

4.2. Erosive Wear - Transport tubes in chemical plants, pumps and valves in hydraulic mining machinery, gun barrels in propellant systems, lock hopper valves, turbines in coal gasification equipment, product steam flow throttle valves in coal liquefaction equipment, economizer tube banks, re-heaters, burner nozzles, super heaters in combustion systems, boiler heat exchanger tubes in expander turbines, bed tubes and tube banks in fluidized bed combustion equipment, blades in aircraft engines, blades in gas turbines, and rotors in helicopter engines are just a few examples of components that are highly exposed to solid particles.

4.2.1. Mechanism of Erosive Wear. Fig. 2 depicts the mechanism underlying erosive wear. The wear rate is determined by the angle and speed at which a particle interacts or impacts the surface. When it comes to round or blunt particles, the surface displays thin, worn material plates that are the result of plastic deformation. If the collision is caused by sharp particles, the consequence is brittle or cutting fragmentation. Any surface that is struck by fragile material will show signs of subsurface breaking. The worn surface occasionally melts as a result of surface particles colliding at extremely high speeds.

The volume displaced by each hit is mostly determined by the hardness, not the volume degraded. As a result, it is unable to offer a strong enough association with erosion rate alone.

Erosion efficiency (η) was thus presented as a measure to get . given as

$$\eta\text{normal} = \frac{2ErHv}{\mathbf{pV^2}}$$

where, Er - erosion rate (Kg/Kg), Hv hardness of eroding material (Pa), ρ - density of the eroding material (kg/m3), V - velocity of impact (m/s).

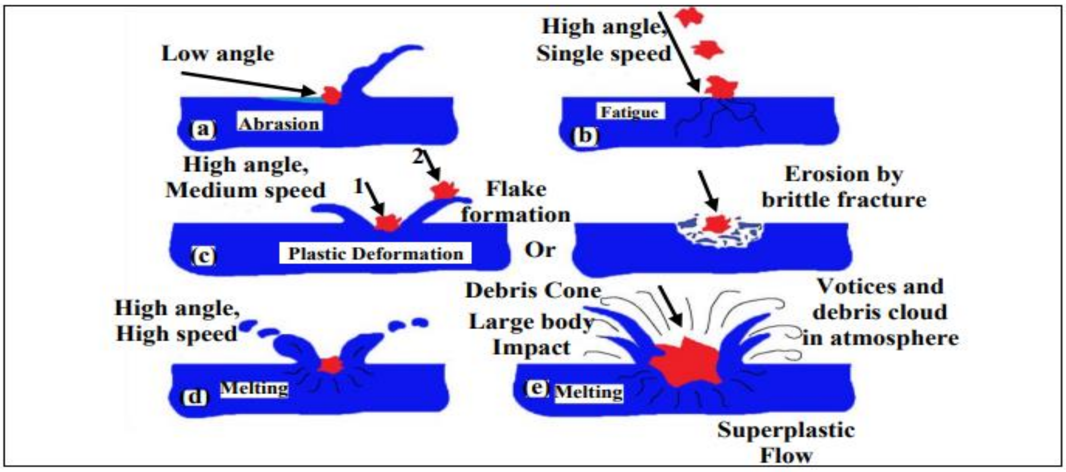
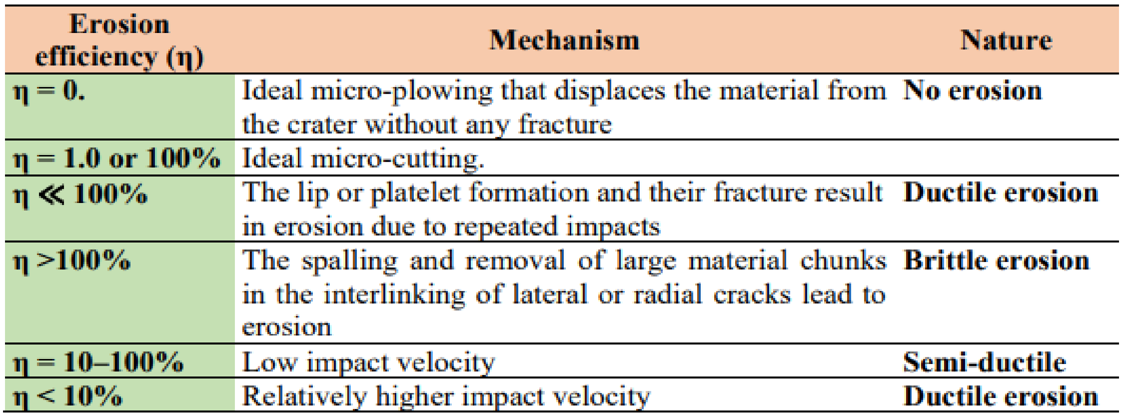


figure 3. Schematic illustrations of erosion wear mechanism

It show that erosion efficiency depends to some extent on other operational aspects, such as impact velocity and impingement edge, and is not solely a material attribute. One can obtain the estimation of η for a specific impact velocity under oblique impact by simply multiplying ηnormal by 1/Sin2∝. Similar observations on the velocity dependence of erosion efficiency have only been made by a small number of researchers in the past. The nature and method of erosion can be explained by the magnitude of η. For varying levels of erosion efficiency (η), Table 1 illustrates the erosion mechanism and its characteristics [151-153].

Table 1. The erosion mechanism and its nature



Erosion efficiency (η)	Mechanism	Nature
η = 0.	Ideal micro-plowing that displaces the material from the crater without any fracture	**No erosion**
η = 1.0 or 100%	Ideal micro-cutting.	
η ≪ 100%	The lip or platelet formation and their fracture result in erosion due to repeated impacts	**Ductile erosion**
η >100%	The spalling and removal of large material chunks in the interlinking of lateral or radial cracks lead to erosion	**Brittle erosion**
η = 10–100%	Low impact velocity	**Semi-ductile**
η < 10%	Relatively higher impact velocity	**Ductile erosion**

4.3. DOE and ANN in Wear

DOE makes it possible to get the best test results and offers a clear knowledge of the mechanisms underlying a complex wear process. A thorough description of several factors and how they interact in various engineering processes, such as wear analysis, was provided by Taguchi's parameter design. This method was used by Rubio et al. [193], Ramesh and Suresha [194], and Vankanti and Ganta [195] to study parameters for least abrasive wear of CF/epoxy composites, as well as the parameters for the optimal drill set up on GF/PA composite and GF/epoxy composites during the drilling process. In addition, using Taguchi's experimental approach, Sahu et al. [196], Gupta and Satapathy [21] carried out wear analyses of fly-ash aluminum coatings and borosilicate-glass microspheres/epoxy composites. Additionally, Patnaik et al. widely employed Taguchi's experimental approach for their assessment of erosion wear [69, 177-182, 197,

5. Conclusion-

The numerous studies done to investigate the impact of fiber reinforcement and filler particles in HPCs for the development of mechanical characteristic performance were thoroughly reviewed. In addition, the author conducted a rigorous analysis of the wear of HPCs that was looked into by several researchers. It was discovered that not much research had been done on the three-body abrasive wear behavior of ceramic-filled HPCs. Furthermore, research on the erosive wear of composites tends to focus less on filler-reinforced systems and more on fiber reinforced polymers. Even though the impact of fillers relative to matrix change is more significant, little study has been done on how particle fillers affect the erosion properties of hybrid composites. Up until now, the wear behavior (erosive wear and three-body wear) has been clearly understood.

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