Erosion wear behavior of oxide fillers reinforced epoxy composites: A Review

Anant K. Pun
Department of Mechanical Engineering
National Institute of Technology, Hamirpur
Himachal Pradesh, India

Harshit Kumar Kaushik
Department of Mechanical Engineering
National Institute of Technology, Hamirpur
Himachal Pradesh, India

Siddhartha
Department of Mechanical Engineering
National Institute of Technology, Hamirpur
Himachal Pradesh, India

Abstract: This paper presents a comprehensive summary of studies carried out by many researchers in the field of solid particle erosion (SPE). The main focus is to present the detailed description about the solid particle erosion of oxide fillers filled epoxy composites and unfilled epoxy composites. In addition to this, the erosion wear behavior of the epoxy composites are also analyzed by using different oxide fillers, ( i.e. Aluminum oxide, titanium dioxide, zinc oxide, chromium oxide etc.). The main focus is on key variables which affect the solid particle erosion that is particle impact velocity, impingement angle, erodent type, erodent size, erodent shape, erodent hardness, erodent temperature and relative fiber orientation. At last, the effect of different oxide fillers on erosion wear behavior of epoxy composite is discussed.

Keywords— Solid particle erosion, polymer matrix composite (epoxy), fiber, oxide fillers.

I. INTRODUCTION

Polymer matrix composites are abundantly used in manufacturing automotive parts such as gears, cams, wheels, brakes, clutches, bearings, transmission belts etc. Erosion wear in all these components is a major industrial problem. Therefore it becomes very important to understand the impact of all the system parameters which leads to the erosion wear [1]. To minimize the effect of erosion wear, various materials such as ferrous materials and non-ferrous materials are widely used. The exhaustive literature survey in this review paper covers the studies on erosion wear behavior of polymer matrix composite using different oxide filler materials at different impingement angle, different impact velocity, different erodent size, shape and type and at different relative fiber orientation [2]. The Polymer matrix composite consists of the matrix material and fiber. Polymers are either thermosetting polymers or thermoplastic polymers and are used as matrix materials. The fibers used in the composite may be natural fiber or synthetic fiber depending upon the requirement. The properties of the composites can be improved by adding materials in the matrix [3]. The main advantage of adding the filler material into the matrix is to improve physical and mechanical properties of the composite, erosion resistance and to reduce the cost [4]. The erosion wear resistance of composites can be improved by adding various fillers such as Aluminum Oxide (Al₂O₃), Silicon Oxide (SiO₂), Titanium dioxide (TiO₂), Fly ash, Borosilicate glass etc. The erosion resistance of polymer matrix composite mainly depends upon the fiber and filler concentration in the composite and the type of oxide fillers used in the composite. To control the erosion wear, it is necessary to know that which filler either oxide or non-oxide, either organic or in-organic is used along with the epoxy composite [5]. Many investigations have been done on the polymer matrix composite because of their versatile properties [5]. Over the years, the conventional materials were chosen for the analysis of erosion wear, but from the last few decades, polymer matrix composites have received the attention of researchers because of their light weight, non-toxic nature, design flexibility, better wear resistance, corrosion resistance, excellent strength to weight ratios and ease of fabrication [5]. That’s why they are used in many fields where high resistance to wear, abrasion and erosion is required such as automobile, aerospace, marine, mining, energetic etc. [6]. They also find applications in the dusty environment such as pipelines carrying sand, slurries in petroleum refining, helicopter rotor blades, pump impeller blades, high-speed vehicles and aircrafts, water turbines, aircraft engine blades, missile components, canopies, radomes,
wind screens and outer space applications [7]. There are various studies about the erosion wear behavior of polymer matrix composite using oxide fillers such as: Mahesha et. al, has studied the solid particle erosion wear behavior of epoxy composite using titanium dioxide (TiO₂) as a filler material. The composites fabricated by vacuum assisted resin infusion technique were tested at different impact velocity(26m/s,40m/s and 62m/s), at different erodent temperature (30°C, 60°C, 90°C and 120°C). The study proved that erosion rate of composite increases with increase in impact velocity and erodent temperature [5]. In another research Bagci et. al. studied the solid particle erosion wear behavior of glass fiber reinforced epoxy composite (GF/EP) using silicon oxide (SiO₂) as a filler material. This study was carried out at three different impingement angle (30°, 60° and 90°), at three different impact velocity (23 m/s, 34 m/s and 53 m/s) and at two different angular aluminum abrasive particles sizes (200µm and 400µm) at the fiber orientation of 45°. The study shows that the erosion rate changes when the experimental condition changes [8].

Tilly [9] gives a brief analysis about the different parameters affecting erosion, including tensile stress, particle properties, particle concentration, material temperature, impact parameters and material temperature. The author also presented the various mechanisms of erosion, which were classified into brittle and ductile behaviors. Ductile erosion usually occurs in the thermoplastic matrix composites while the brittle erosion generally found in the thermosetting matrix composites. Khadhim et. al. [10] represented a thorough analysis of the erosion wear behavior of micro material reinforced polymer composites. It was found that the non-reinforced epoxy have lower resistance to erosion than micro based material composites and the specimen with fillers has higher resistance to erosion than industrial based material composites. The erosion resistance increases with increase in the volume fraction of filler materials.

II. PARAMETERS AFFECTING SOLID PARTICLE EROSION

Erosion wear is described as progressive loss of the material from the solid surface due to the interaction between the surface and the erodent particle. The removal of material during the erosion wear mainly depends upon the properties and structures of the target materials. In addition to it, Impact velocity, angle of impingement, erodent type, erodent size, erodent shape, erodent hardness, erodent temperature, erodent feed rate, relative fiber orientation are also envisaged as important variables affecting the erosion wear. Any variation in any of these parameters may cause a change in erosion resistance of the material [11].

III. EROSION WEAR OF POLYMER MATRIX COMPOSITES

The erodent (abrasive particles) coming out from the nozzles having high velocity and when the erodent strikes the surface of the target material it causes rise in temperature of the target surface thereby softening the matrix to an extent making the target material more prone to deformation [10]. The moment when particle strikes the target surface, the kinetic energy of the particle is transferred to the polymer matrix composite which creates a crater and hence erosion wear occurs [12]. The behavior of erosion wear of the polymer matrix composite can be classified into two categories namely ductile and brittle manner. Ductile erosion usually occurs in the thermoplastic matrix composites while the brittle erosion generally observed in the thermosetting matrix composites.

Erosion wear is one of the major industrial problem that causes structure damage. Erosion wear mainly occurs in the automobile industries, offshore industry etc. In offshore industries, solid particles are entrapped during the fluid flow in oil and gas pipelines, gas turbines etc. causes pitting action and hence the erosion wear takes place [10].

IV. EROSION WEAR BEHAVIOR OF DIFFERENT OXIDE FILLER BASED POLYMER COMPOSITES

A. Aluminium Oxide as a filler

Use of Aluminium Oxide as a filler material in the epoxy resin increases the erosion resistance of the polymer matrix composite. It is well known that the composite without filler materials undergoes high erosion wear as compared to the composites using filler materials. Khadhim et. al. (2016) studied the erosion wear behavior of polymer matrix composite constituted of epoxy, glass fiber, and aluminum oxide as a filler material. The key results were obtained by varying the weight percentage of aluminum oxide in the epoxy composite [10].
Table 1 Erosion wear of pure epoxy, epoxy + 3% glass fiber + 2% aluminum oxide, epoxy + 3% glass fiber + 4% aluminum oxide and epoxy + 3% glass fiber + 6% aluminum oxide [10]

<table>
<thead>
<tr>
<th>Filler Content</th>
<th>Impingement angle(°)</th>
<th>Grain Size (µm)</th>
<th>Temperature (°C)</th>
<th>Erosion rate (cm³/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure epoxy</td>
<td>30</td>
<td>425</td>
<td>25</td>
<td>0.074</td>
</tr>
<tr>
<td>Pure epoxy</td>
<td>60</td>
<td>600</td>
<td>30</td>
<td>0.076</td>
</tr>
<tr>
<td>Pure epoxy</td>
<td>90</td>
<td>850</td>
<td>35</td>
<td>0.078</td>
</tr>
<tr>
<td>Epoxy + 3% GF + 2% micro Al2O3</td>
<td>60</td>
<td>425</td>
<td>35</td>
<td>0.0066</td>
</tr>
<tr>
<td>Epoxy + 3% GF + 2% micro Al2O3</td>
<td>90</td>
<td>600</td>
<td>25</td>
<td>0.0067</td>
</tr>
<tr>
<td>Epoxy + 3% GF + 2% micro Al2O3</td>
<td>30</td>
<td>850</td>
<td>30</td>
<td>0.0068</td>
</tr>
<tr>
<td>Epoxy + 3% GF + 4% micro Al2O3</td>
<td>60</td>
<td>425</td>
<td>35</td>
<td>0.0060</td>
</tr>
<tr>
<td>Epoxy + 3% GF + 4% micro Al2O3</td>
<td>90</td>
<td>600</td>
<td>25</td>
<td>0.0062</td>
</tr>
<tr>
<td>Epoxy + 3% GF + 4% micro Al2O3</td>
<td>30</td>
<td>850</td>
<td>30</td>
<td>0.0063</td>
</tr>
<tr>
<td>Epoxy + 3% GF + 6% micro Al2O3</td>
<td>60</td>
<td>425</td>
<td>35</td>
<td>0.0056</td>
</tr>
<tr>
<td>Epoxy + 3% GF + 6% micro Al2O3</td>
<td>90</td>
<td>600</td>
<td>25</td>
<td>0.0058</td>
</tr>
<tr>
<td>Epoxy + 3% GF + 6% micro Al2O3</td>
<td>30</td>
<td>850</td>
<td>30</td>
<td>0.0059</td>
</tr>
</tbody>
</table>

While fig2(b) shows the variation of erosion rate by varying the impingement angle at three different impact velocities for silicon oxide filled GF/EP at fiber orientation of 45° for 200µm [8].

B. Silicon Oxide as a filler

The main purpose of using the silicon oxide as a filler material is to reduce the expenses and to improve the material strength. Bagci et. al. (2011) has compared the erosion wear behavior of neat epoxy having glass fiber only and the silicon oxide filled GF/EP. Fig 2 shows the erosion wear behavior of GF/EP (neat) and silicon oxide filled GF/EP. Fig 2(a) shows the variation of erosion rate by varying the impingement angle at three different impact velocities (i.e. 23 m/s, 34 m/s and 53 m/s) for GF/EP (neat) at fiber orientation of 45° for 200µm.
Fig 3: Impingement angle v/s erosion rate at impact velocities of 23, 34 and 53 m/s and at fiber orientation of 45° for 400 µm: (a) GF/EP (Unfilled), (b) GF/EP (Silicon Oxide)

Fig 3(a) shows the variation of erosion rate by varying the impingement angle at three different impact velocities (i.e., 23 m/s, 34 m/s and 53 m/s) for GF/EP (neat) at fiber orientation of 45° for 200µm. While fig 3(b) shows the variation of erosion rate by varying the impingement angle at three different impact velocities for silicon oxide filled GF/EP at fiber orientation of 45° for 200µm.

From the Fig 3, it is clear that with the addition of Silicon oxide in the matrix, erosion rate decreases and the erosion resistance increases as compared to the neat GF/EP.

C. Titanium dioxide as a filler

Fig 4 shows the variation of impingement angle at different impact velocities for glass epoxy (neat) and glass epoxy(titanium dioxide filled). Vijay et. al. (2016) performed the Air Jet Erosion Test and on the basis of the test, they could find that weight loss of the GE composite decreases with increase in the impingement angle for both class of composite (oxide filler filled and neat GE). But for titanium dioxide filled epoxy composite, weight loss is less than the neat GE [13].

Fig 4: Weight loss v/s impingement angle at impact velocities of 23, 34 and 53 m/s: (a) Glass epoxy (unfilled); (b) Glass epoxy (TiO2 filled) [13].

From the above two figure, it is clear that the rate of erosion is high for unfilled glass epoxy composite whereas erosion rate is much lower for TiO2 filled glass epoxy composite for different impingement angle at any impact velocity.

D. flyash as a filler

V. K. Srivastava et. al. had experimented to study the effect of fly ash as a filler material to the polymer matrix composite. They used silica sand as an erodent having size ranges from150-250µm. And then they studied the erosion wear behaviour of fly ash filled epoxy composite by varying the impingement angle from 30°-90° and at different impact velocity such as 24m/s, 35 m/s and 52m/s [14].

Fig 5 shows the variation of erosion rate by varying the cumulative weight of erodent at different impingement angle for the impact velocity of 24 m/s. These graphs helps to arrive at conclusion that the erosion rate first decreases up to some value and then it increases and becomes constant after some value.

The erosion rate for unfilled glass epoxy composite is always higher as compared to flyash filled GFRP composite. But the value of erosion rate for 4g flyash filled GFRP is slightly lower than that of 2g flyash filled GFRP.

E. Borosilicate glass as a filler

Borosilicate consists of silica, boric oxide and few amount of alkali such as potassium oxide and sodium oxide. Gaurav Gupta et. al. (2014) found a good result using borosilicate glass microspheres as a filler material to the polymer matrix composite. Borosilicate glass microsphere possesses versatile properties such as higher thermal stability, high specific compressive strength and low moisture absorption. It is also having good corrosion resistance, thermal resistance and wear resistance [15].
As presented by the Gaurav Gupta, the above table shows that the use of hard solid borosilicate glass microspheres increases the erosion resistance of the epoxy composites.

F. Red mud as a filler

Red mud is a major industrial waste during the production of alumina from bauxite by Bayer’s process. And it has very good properties to be used as a filler material in polymeric matrices [16]. The primary constituents of red mud are as follows: \( \text{Fe}_2\text{O}_3 \) 20-60\%, \( \text{Al}_2\text{O}_3 \) 10-30\%, \( \text{SiO}_2 \) 2-20\%, \( \text{Na}_2\text{O} \) 2-10\%, \( \text{CaO} \) 2-8\%, \( \text{TiO}_2 \) traces 2-8\% [17].

Niharika and Acharya (2015) have studied the erosion wear behavior of red mud filled glass fiber reinforced epoxy composite. Fig.5 shows the variation of erosion rate by varying the impingement angle at 82m/s impact velocity for unfilled GFRP and red mud filled GFRP. The graph shows that the maximum erosion occurs at impingement angle of 60° [18].

**Table 2 Erosion rate at different experiment conditions**

<table>
<thead>
<tr>
<th>Impact Velocity (m/s)</th>
<th>Impingement angle (°)</th>
<th>Erodent Size (µm)</th>
<th>Erodent temp. (°C)</th>
<th>Filler Content (wt%)</th>
<th>Erosion rate (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>30</td>
<td>50</td>
<td>30</td>
<td>0</td>
<td>1.288</td>
</tr>
<tr>
<td>32</td>
<td>45</td>
<td>100</td>
<td>60</td>
<td>10</td>
<td>1.293</td>
</tr>
<tr>
<td>32</td>
<td>60</td>
<td>150</td>
<td>90</td>
<td>20</td>
<td>0.987</td>
</tr>
<tr>
<td>32</td>
<td>90</td>
<td>200</td>
<td>120</td>
<td>30</td>
<td>0.803</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>50</td>
<td>30</td>
<td>30</td>
<td>1.327</td>
</tr>
<tr>
<td>40</td>
<td>45</td>
<td>100</td>
<td>60</td>
<td>20</td>
<td>1.354</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>150</td>
<td>90</td>
<td>10</td>
<td>1.370</td>
</tr>
<tr>
<td>40</td>
<td>90</td>
<td>200</td>
<td>120</td>
<td>0</td>
<td>1.422</td>
</tr>
<tr>
<td>48</td>
<td>30</td>
<td>50</td>
<td>30</td>
<td>10</td>
<td>1.368</td>
</tr>
<tr>
<td>48</td>
<td>45</td>
<td>100</td>
<td>60</td>
<td>0</td>
<td>1.415</td>
</tr>
<tr>
<td>48</td>
<td>60</td>
<td>150</td>
<td>90</td>
<td>30</td>
<td>1.281</td>
</tr>
<tr>
<td>48</td>
<td>90</td>
<td>200</td>
<td>120</td>
<td>20</td>
<td>1.384</td>
</tr>
<tr>
<td>56</td>
<td>30</td>
<td>50</td>
<td>30</td>
<td>20</td>
<td>1.431</td>
</tr>
<tr>
<td>56</td>
<td>45</td>
<td>100</td>
<td>60</td>
<td>30</td>
<td>1.356</td>
</tr>
<tr>
<td>56</td>
<td>60</td>
<td>150</td>
<td>90</td>
<td>0</td>
<td>1.447</td>
</tr>
<tr>
<td>56</td>
<td>90</td>
<td>200</td>
<td>120</td>
<td>10</td>
<td>1.415</td>
</tr>
</tbody>
</table>
Fig 6: Variation of erosion rate with different impingement angle at 82 m/s impact velocity.

G. Linz-Donawitz as a filler
Linz-Donawitz slag is a major solid waste generated in huge quantities during steel making. It is generated from slag formers such as dolomite/burned lime and from oxidizing of iron, silica etc. during refining of iron into steel in the Linz-Donawitz furnace. The major constituents of the Linz-Donawitz slag are iron oxide, silicon oxide and calcium oxide [19]. Pravat and Satapathy (2013) performed the experiment by taking Linz-Donawitz as a filler material in the epoxy composite. Fig. 6 shows the variation of erosion rate by varying the impact velocity [20].

Fig 7: Variation of erosion wear rate with impact velocity

H. Using Cement By-Pass Dust (CBPD) as a filler
Cement By-Pass Dust (CBPD) is a byproduct generated during cement manufacturing. It is a fine powder and similar to Portland cement in appearance. It is generated during the calcining process in the kiln. The major constituents of CBPD are CaO, SiO₂, Al₂O₃, Fe₂O₃, K₂O, Na₂O etc. Gupta et. al. (2011) studied the erosion wear behavior of Cement By-Pass Dust (CBPD) filled bamboo fiber composites. The key results were obtained by varying the weight percentage of the Cement By-Pass Dust (CBPD) in the bamboo fiber reinforced epoxy composite. Fig 7 shows the effect of impingement angle on erosion rate for unfilled epoxy composite and unfilled epoxy composite at an impact velocity of 45 m/s and erodent size of 250 µm. The graph shows that the erosion rate of unfilled epoxy composite is greater than the CBPD filled epoxy composite irrespective of impingement angles [21].

Fig 8: (a) Effect of impact velocity on erosion rate of the composites; (b) Effect of impingement angle on erosion rate of the composites.

I. Copper slag as a filler
Copper slag is an industrial waste and it is generated as a byproduct during the smelting and refining of copper. During the production of one ton copper, approximately 2.2-3 tons of copper slag generates. Copper slag is rich in various metal oxides, and it has very good properties to be used as a filler material in polymeric matrices. Sandhyarani (2014) studied the erosion wear behavior of Copper Slag Filled Short Bamboo Fiber Reinforced Epoxy Composites. Fig 9 shows the effect of impingement angle on erosion rate for unfilled epoxy and copper slag filled epoxy composite. The graph shows that the maximum erosion takes place at an impingement angle of 60° for all the samples [22].

Fig 9: Effect of impingement angle on erosion rate of copper slag filled Composites.
V. EFFECT OF EXPERIMENTAL CONDITIONS ON EROSIIVE WEAR

There are many test parameters which significantly affects the erosion wear behavior of polymer matrix composite. These parameters are impact velocity, angle of impingement, erodent shape, erodent hardness, size of erodent, erodent type, erodent temperature, relative fiber orientation etc.

I) Effect of Impingement Angle – Angle of Impingement plays an important role in the erosion wear. By varying the impingement angle (i.e. 30°, 45°, 60°, 90° etc), the rate of erosion also changes. As the impingement angle increases, the erosion rate decreases.

II) Effect of Impact velocity – Impact velocity is known as the velocity of erodent with which it hits the surface. Erosion rate mainly depends upon the impact velocity. As the impact velocity increases, the erosion rate also increases.

III) Effect of Erodent temperature - Loss of material from the surface occurs when the erodent strikes the surface with some velocity. But when the temperature of the erodent particles is greater than that of the temperature of the target surface, then it causes more material loss from the target surface.

IV) Effect of fiber orientation – Fibre orientation means how the fibre is reinforced in the composite either it is across the impingement direction or it is along the impingement direction. Many researches have been carried out on the basis of 0°, 45° and 90° fibre orientation.

V) Effect of Erodent shape, type and size – Size, shape and type of erodent plays another important role in the study of erosion wear behavior.

VI. CONCLUSION

The aim of this review paper is to compare the erosion rate of epoxy composites using different oxide fillers at different operating conditions.

1. Use of Titanium dioxide (TiO₂) in epoxy composite gives higher erosion resistance as compared to unfilled epoxy composites. And the erosion wear mainly depends upon the impact velocity and the erodent temperature.

2. Silicon Oxide filled composite shows lower wear as compared to the unfilled composites. i.e. addition of SiO₂ particles gives positive effects on the erosion wear and increases the erosion resistance.

3. From the table 1, it can be seen that the specimen having aluminium oxide (Al₂O₃) shows better erosion resistance as compared to the pure epoxy. And as the amount of aluminium oxide (Al₂O₃) in the epoxy composite increases, the erosion resistance increases simultaneously. Epoxy composite with 3% glass fibre and 6% micro aluminium oxide (Al₂O₃) gives very high erosion resistance at a temperature of 35°C and at an impingement angle of 60°.

4. Addition of flyash filler in the glass fibre reinforced polymer composite reduces the density, hardness and the tensile strength. And the material having high hardness will also have high erosion rate. The specimen without any filler (glass epoxy) shows very high erosion rate whereas the specimen having flyash as a filler material shows slightly less erosion rate as compared to the pure epoxy. And as the amount of filler material increases in the epoxy composite, the erosion resistance increases. Hence the specimen having 4g flyash gives very high erosion resistance.

5. Using borosilicate glass as a filler material to the epoxy composite, erodent size has negligible effect on the wear rate. And from the table 2, it is clear that the addition of hard solid borosilicate glass micro-spheres increases the erosion resistance of the composite.

6. Using Red mud as a filler material to the GFRP composites improves the density and hardness but reduces the tensile strength. GFRP composite having 25% red mud shows very high erosion resistance and the maximum erosion occurs at the impingement angle of 60°.

7. Addition of LD slag as filler material shows very high erosion resistance and the erosion wear reduces with increase in the amount of LD slag in epoxy composite.

8. CBPD shows very high potential to be used as a filler material to the epoxy composites. Erosion resistance increases with the addition of CBPD. Maximum erosion occurs at the impingement angle of 60°.

9. Copper slag filled epoxy composites shows very high erosion resistance as compared to the unfilled epoxy composites. Apart from the copper slag, other factors like impingement angle, amount of fiber/filler material, impact velocity etc. has a great impact on the erosion wear. The maximum erosion wear occurs at the impingement angle of 60°.

References


