Solid particle erosion of carbon fibre- and glass fibre-epoxy composites

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Abstract

The solid particle erosion behaviour of unidirectional carbon and glass fibre reinforced epoxy composites has been characterized. The erosive wear of these composites have been evaluated at different impingement angles (15-90°) and at three different fibre orientations (0, 45, and 90°). The particles used for the erosion measurements were steel balls with diameter of 300-500 mm and impact velocity of 45 m/s. The unidirectional carbon and glass fibre reinforced epoxy composites showed semi ductile erosion behaviour, with maximum erosion rate at 60° impingement angle. The fibre orientations had a significant influence on erosion. The morphology of eroded surfaces was examined by using scanning electron microscopy (SEM). Possible erosion mechanisms are discussed.

Keywords: Polymer-matrix composites (PMCs); Debonding; Solid particle erosion; Fibre orientations; Scanning electron microscopy (SEM)

1. Introduction

If solid particles impinge against a target surface and cause local damage combined with material removal, this kind of wear is generally referred to as erosion [1]. Polymer composite materials have generated wide interest in various engineering fields, particularly in aerospace applications, because they exhibit high specific strength and stiffness as compared to monolithic metal alloys. Polymer composite materials are therefore finding increased application under conditions in which they may be subjected to solid particle erosion. Examples of such applications are pipe line carrying sand slurries in petroleum refining, helicopter rotor blades [2,3], pump impeller blades, high speed vehicles and aircraft operating in desert environments, water turbines, and aircraft engine blades [4]. However, polymer composite materials exhibit poor erosion resistance as compared to metallic materials [5]. It is also known that the erosive wear of polymer composites is usually higher than that of the unreinforced polymer matrix [6].

Solid particle erosion of polymers and their composites has not been investigated to the extent that it has for metals or ceramics. Many researchers [1-26] have evaluated the resistance of various types of polymers and their composites to solid particle erosion. Materials that have been eroded include nylon [7,8], epoxy [5,19,20], polypropylene [13,16], polyethylene [14], UHMWPE [26], PEEK [15,18] and various polymer based composites [1,2,5-26]. The erosion experiments carried out by the various investigators with different polymer composites are listed in Table 1 along with experimental conditions.

Erosive wear resistance of polymers and their composites is therefore of substantial interest. From literature survey it is evident that very little work has been reported on solid particle erosion studies of epoxy and their composites [5,19,20]. Unidirectionally reinforced fibre composites represent the basic element of complex composite structures. Therefore, study of their behaviour is an important component of the analysis of erosive wear of polymer composites. The objective of the

Table 1
Details of erosion experiments carried out on polymer/polymer matrix composites by various investigators

Material tested	Test conditions	Type of erodent, shape and size used	Ref.
Glass epoxy resin, glass phenolic resin (modified), glass phenolic resin (unmodified) and glass polyester resin	F=38±5, 45 ± 5 m/s a = 30°, 90°	Silica sand, angular, 200 ±50 *mm*	[5]
Unidirectional glass, carbon and aramid reinforced composites with epoxy, PEEK and PEKK matrix	V=85m/s a =15°, 30°, 60°, 90°	Corundum particles, angular, 400 mm	[6]
Quartz polybutadiene, glass cloth epoxy and quartz polyimide composites	V=42m/s a = 30°, 45°, 60°, 75°, 90°	Natural sea sand, slightly rounded, 210-297 mm	[9]
Bismaleimide (BMI) matrix and reinforced with graphite fibre	V=20, 40, 60 m/s a = 30°, 90°	Alumina oxide particles, angular, 63, 130 and 390 mm	[11]
Bismaleimide (BMI) matrix	V=60 m/s a = 90°	Alumina oxide particles, angular, 42, 63, 143 and 390 mm	[12]
Polystyrene, polyethylene, polypropylene, polybutene	V=57m/s a = 90° Room temperature and -35 °C	Steel balls, spherical, diameter of 500 mm	[1]
Nylon 66, Nylon 6, ABS reinforced with short glass, carbon fibres, Thermoset resin unsaturated polyester and epoxy reinforced by woven glass cloth	*V*= 23,29,35,47 m/s a =15°, 30°, 45°, 60°, 90°	SiC abrasives, irregular, 100-150 mm	[17]
Thermoplastic polyimide, PEEK matrix and reinforced with glass, carbon fibres	V=17, 34, 56.7 m/s a =15°, 30°, 45°, 60°, 90°	SiC abrasives, irregular, 100-150 mm	[18]
Epoxy and reinforced with unidirectional carbon fibres	V=18.9, 34.6, 55.7 m/s a =15°, 30°, 45°, 60°, 90°	SiC abrasives, irregular, 100-150 mm	[19]
Epoxy matrix and reinforced with unidirectional glass fibre	V=70m/s a = 30°, 60°, 90°	Corundum particles, angular, 60-120 mm	[20]
Polypropylene matrix and reinforced with discontinuous short, long glass fibre and continuous unidirectional glass fibre	V=70m/s a = 30°, 60°, 90°	Corundum particles, angular, 60-120 mm	[25]
Ultra high molecular weight polyethylene (UHMWPE)	*V*= 10,20,40,70, 100 m/s a =15°, 30°, 45°, 60°, 75° and 90°	Coal powder, silicon dioxide, angular, 60-70 mesh size	[27]

V, impact velocity (m/s); *a*, impact angle (°).

present investigation was to study the solid particle erosion characteristics of unidirectional carbon and glass fibre reinforced epoxy composites under various experimental conditions. Another aim was to study the effect of relative fibre orientation on erosive wear behaviour. In the present study steel balls of 300-500 urn were used as erodent. In most practical situations erosive wear particles are irregular dust grains of much lower density than steel. The steel balls were used because this implies higher energy by single impact. The present testing condition was used, even though it is unusual, because the objective was to carry out a fundamental study of erosion and to investigate the effect of fibre orientation in composites on steel ball impact.

2. Experimental details

2.1. Materials

RIGIDITE 5212 and 5217 epoxy prepreg system (BASF) reinforced with unidirectional celion G 30-500 carbon fibres and glass fibres were used in the preparation of carbon and glass fibre reinforced epoxy composites respectively. Panels of 30 x 30 cm consisting of 14 and 20 plies were laminated by hand and cured according to manufacturer instruction under 95% vacuum. Composites were characterized by using various analytical methods. The glass transition temperature (T_g) was determined by using differential scanning calorimeter (DSC mettler Thermal Analyser) at a heating rate of

10 °C/min in N_2 atmosphere. Fibre volume fraction *(Vf)* was estimated by density measurements. The densities of composites were measured by weighing samples in ethanol. Fibre volume fraction was then calculated from known densities of components. The hardness *(H_v)* of the composites was obtained at 1 kg load by using a Vickers hardness tester. Table 2 provides the properties of the unidirectional carbon and glass fibre reinforced epoxy composites.

2.2. Erosive wear test rig

The room temperature erosion test facility used in the present investigation is illustrated schematically in Fig. 1. The particles are driven by a static pressure *P* and are accelerated along a 80 mm long nozzle of 8 mm diameter. The velocity of the eroding particles is determined using the rotating disc method [27]. The distribution of average particle velocities and mass flow throughout the flow cross section were obtained for several values of pressure *P* at various distances from the nozzle tip. It was found that the average velocity at higher pressures is rather uniformly distributed within a 15 mm distance around the flow axis. However, the mass flow decreases substantially with distance from the flow axis. A pressure of 4 bar was used in erosion testing. The average velocity of steel ball at this pressure at 160 mm from nozzle tip was 45 ±5 m/s. The specimens were subjected to a particle flow at a given impingement angle and angle of fibre orientation (Fig. 2). Wear was measured by weight loss after each 15 s of erosion. Samples of 30 mm x 30 mm x 3 mm were cut from the composites and mounted in the specimen holder by 2 mm thick steel cover plate with a hole of 30 mm in diameter. The conditions under which the erosion tests were carried out are listed in Table 3.

Table 2
Properties of composites used

Composites	Glass transition temperature, T_g (°Q	Density (g/cm^3)	Fibre volume fraction, V_f (%)	Vickers hardness, H_v (kg/cm^2)
CF/EP	149	1.51	56	40.7
GF/EP	137	1.88	53	63.7

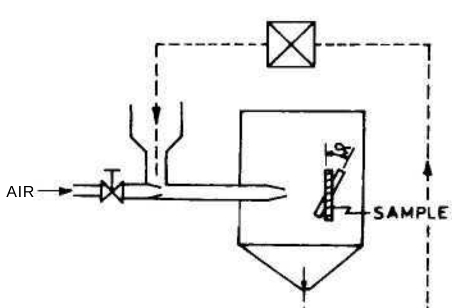


Fig. 1. Schematic diagram of erosion rig.

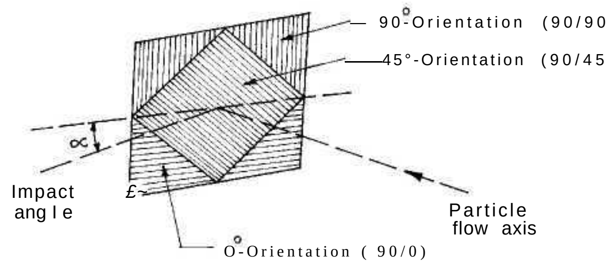


Fig. 2. Definition of impingement angle and fibre orientations.

2.3. Characterization of eroded samples

To characterize the morphology of eroded surface and to understand the mode of material removal, the eroded samples were observed under scanning electron microscope (Philips 515). The samples were gold sputtered in order to reduce charging of the surface.

3. Results and discussion

Fig. 4(a) and (b) show the influence of impingement angle, fibre orientation on erosive wear of CF/EP and GF/EP respectively. The weight loss of CF/EP and GF/EP as function of exposure time at impingement angle of 60° for three fibre orientations is shown in Fig. 5(a) and (b). Fig. 6 shows comparative erosive wear performance of CF/EP and GF/EP at different impingement angles. SEM micrograph of worn samples are shown in Figs. 8 and 9.

Table 3
Erosion test conditions

Test parameters	
Erodent	Steel balls
Erodent size (μm)	300-500
Erodent shape	Round
Vickers hardness of erodent *(H_v)* (kg/cm^2)	400-800
Density of steel ball (g/cm^3)	7.8
Impingement angles	15-90°
Impact velocity (m/s)	45 ±5,
Fibre orientations	0° (90/0), 45° (90/45), 90° (90/90)
Erodent feed rate (g/s)	15
Test temperature	RT
Nozzle to sample distance (mm)	160

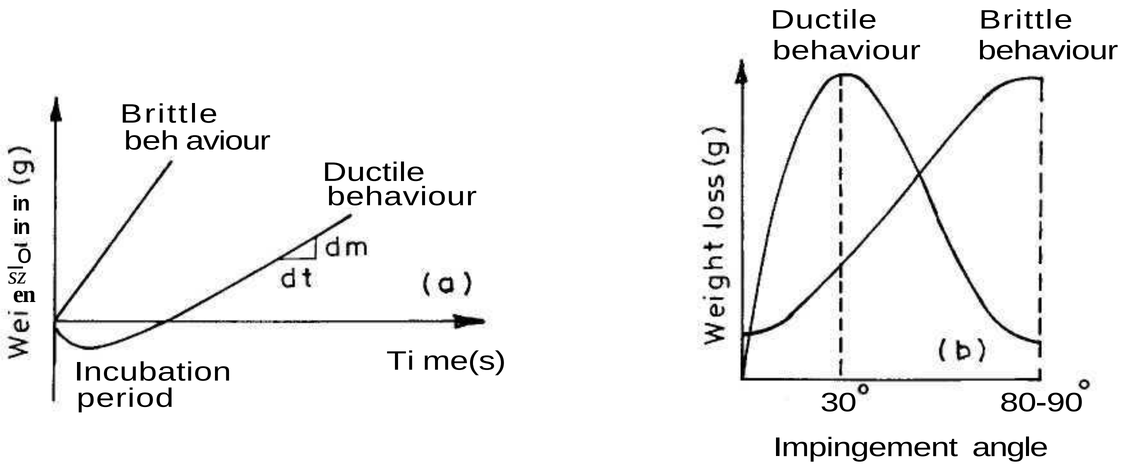


Fig. 3. Schematic representations of brittle and ductile type of erosive wear [20].

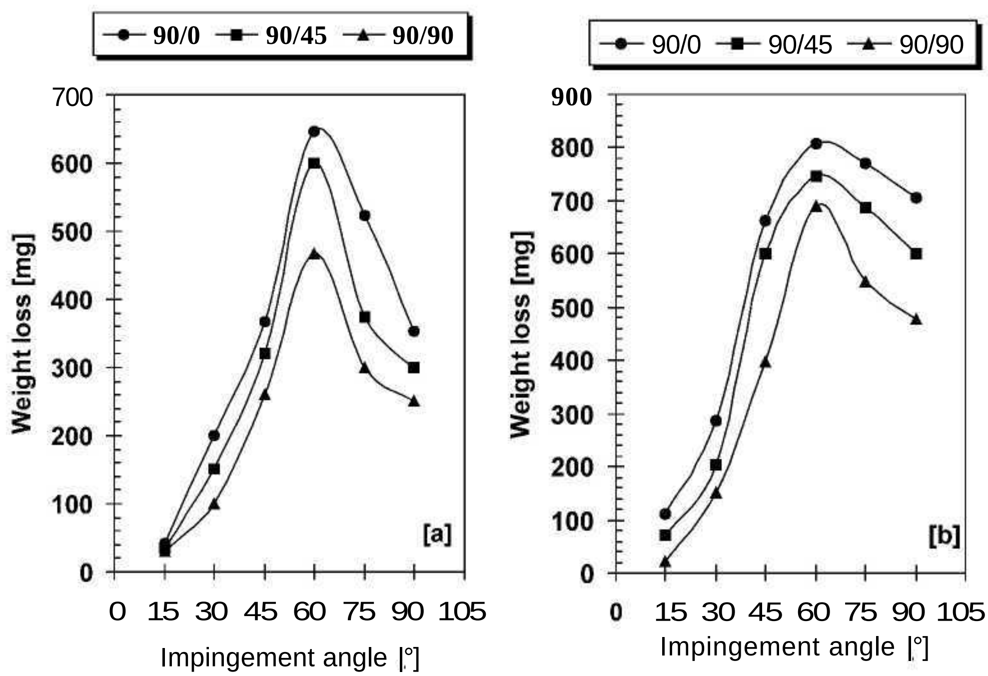


Fig. 4. Influence of impingement angle, fibre orientations on the erosive wear of (a) CF/EP (b) GF/EP composites (v = 45±5 m/s, steel balls diameter = 300-500 mm, exposure time= 180 s].

3.1. Effect of impingement angle

The angle of impingement is usually defined as the angle between the eroded surface and the trajectory of the particle immediately before impact. Fig. 3 shows schematic representation of typical erosion diagram as a function of impact time and impingement angle respectively. The most important factors influencing the erosion rate of materials are the impact angle, impact velocity, the size, shape and hardness of eroding particles [28]. When the erosion weight loss was measured as a function of impingement angle, ductile and brittle materials have shown a marked difference in their response [29]. The behaviour of ductile materials is characterized by maximum erosion at low impingement angles (15-30°). Brittle materials, on the other hand, show maximum erosion under normal impingement angle (90°). Reinforced composites, unlike the above two categories, have been shown to exhibit a semi ductile behaviour with maximum erosion occurring in the range of 45-60° [6,9,17].

Fig. 4(a) and (b) show the influence of impingement angle, fibre orientation on erosive wear of CF/EP and GF/EP respectively. It can be seen that the weight loss was maximum at 60° impingement angle for all fibre orientations for both materials. This is semi ductile

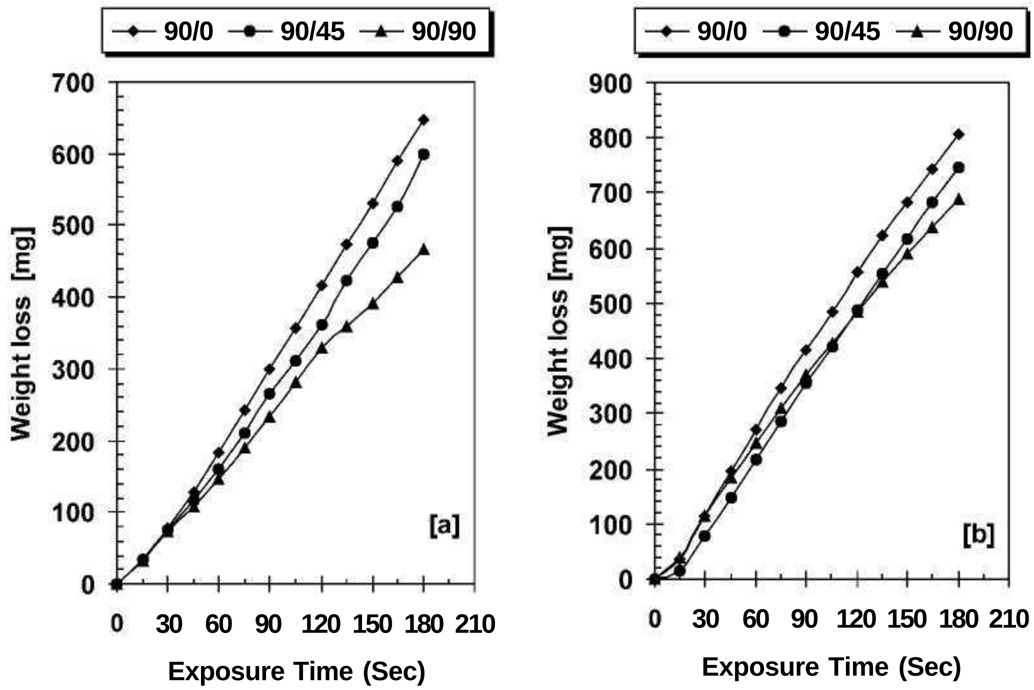


Fig. 5. Weight loss as a function of exposure time (a) CF/EP (b) GF/EP (impingement angle =60°; v = 45±5 m/s; steel balls diameter = 300-500 μm).

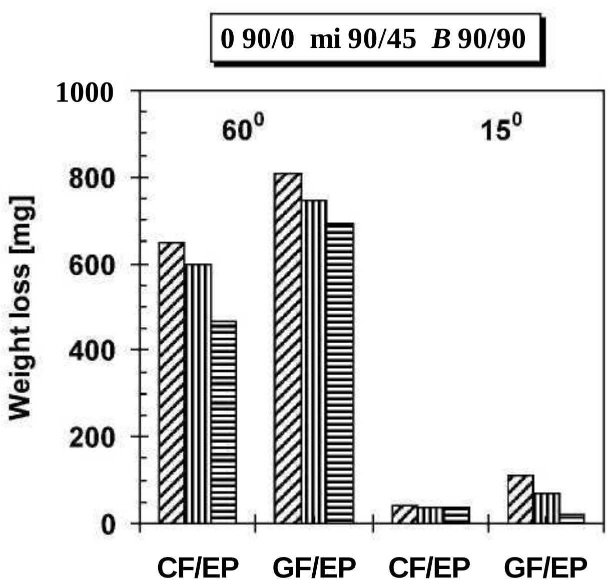


Fig. 6. Comparison of weight loss at different impingement angles for CF/EP and GF/EP (v = 45±5 m/s; steel balls diameter = 300-500 mm; exposure time = 180 s].

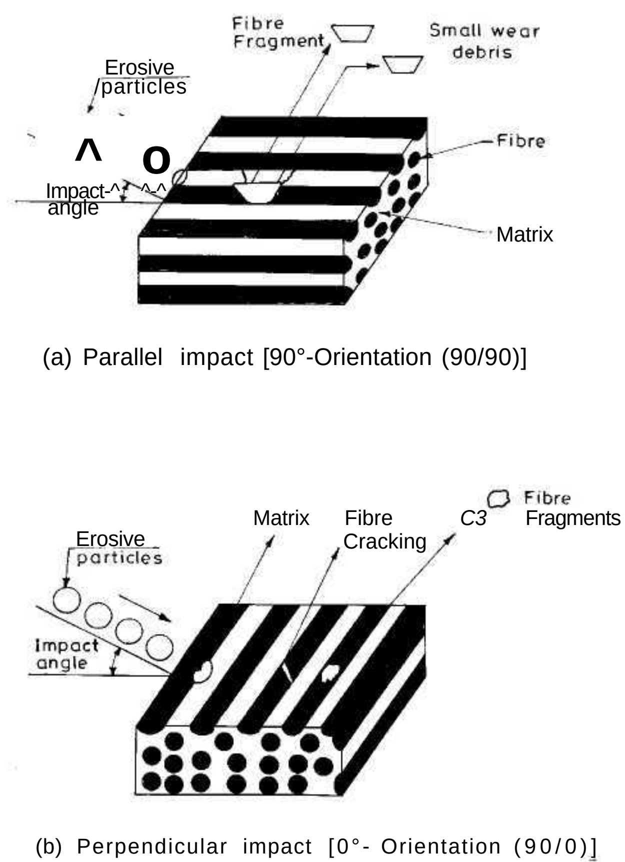
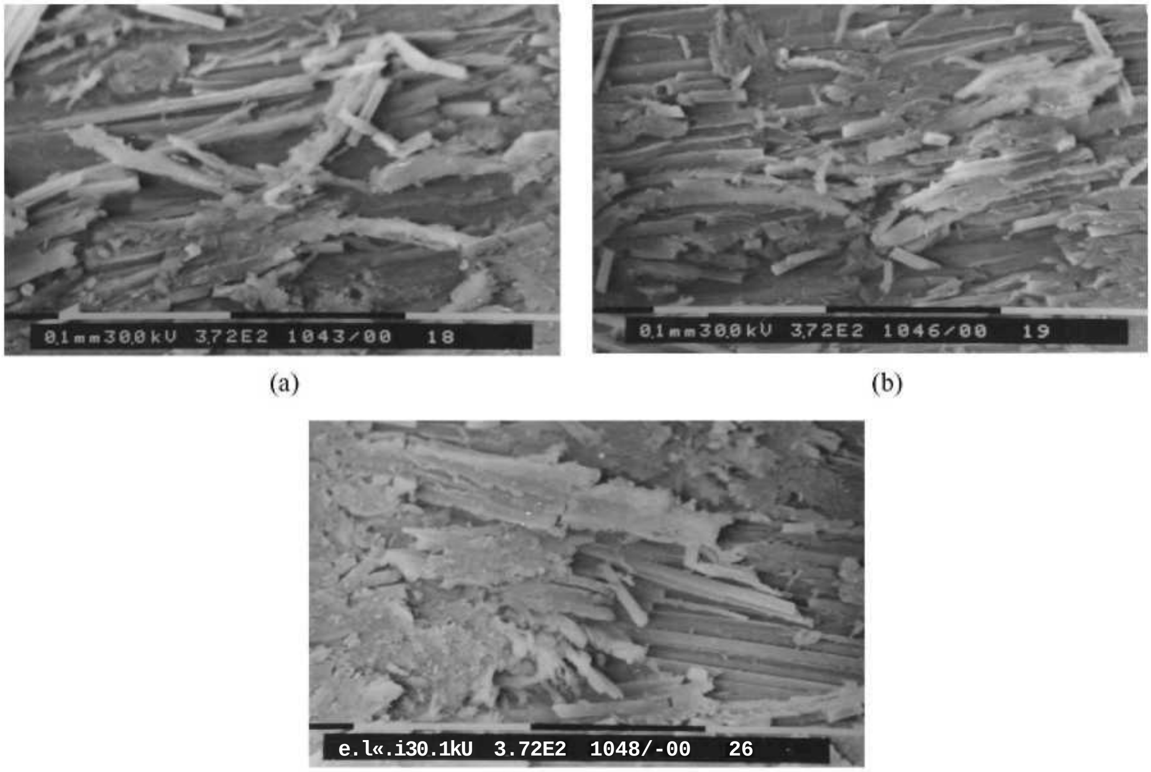


Fig. 7. Schematic diagrams of erosive process in unidirectional fibre reinforced composites under parallel and perpendicular impact conditions.

erosion behaviour. The shapes of the curves are similar in both cases. The effect of fibre orientation is more pronounced at the higher impingement angle. The order of performance at 60° impingement angle was 90/0 (0° fibre orientation) > 90/45 (45° fibre orientation) > 90/90 (90° fibre orientation).

Table 1 provides details of erosion experiments carried out by various investigators. Many investigators



(a) (b)

(C)

Fig. 8. SEM micrographs of CF/EP, composite eroded with steel balls of diameter = 300-500 μm; v = 45 ± 5 m/s; exposure time = 180 s; impingement angle = 60° (a) 0° (b) 45° (c) 90° fibre orientations.

have used angular silica sand, alumina, corundum particles or irregular silicon carbide (SiC) abrasives. In the present study steel balls were used as erodent. Tsiang [10] carried out sand erosion testes on a wide range of thermosets and thermoplastic polymer matrix composites having glass, graphite, and Kevlar fibres in the forms of tape, fabric and chopped mat as reinforcements. In this study, the author concluded that, in GF/EP, as well as in all other composites with thermoset matrix, the erosion showed brittle behaviour, while in composites with a thermoplastic matrix semi-ductile erosion was dominant. Manish Roy et al. [5] reported that composites having a thermoset matrix (epoxy and phenolic) behave in a brittle way while the composites with thermoplastic matrix (polyester) respond in ductile manner. Hager et al. [6] investigated solid particle erosion behaviour of both thermoset and thermoplastic composites by using corundum particles. The maximum erosion rate was observed at an angle of impingement of 60°, for all materials tested except AF/EP. Zahavi et al. [9] reported similar observation for E-glass/EP composites.

In the erosion tests, plastics show ductile nature, and it is known [30,31] that ductile materials have a peak erosion rate around 30° because cutting mechanism is dominant in erosion. Also Miyazaki and Hamao [19] reported peak erosion rate for unreinforced epoxy resin at around 30°. A possible reason for the erosion behaviour in the present study is that the glass and carbon fibres used as reinforcement for epoxy matrix are a typical brittle materials, so that erosion is mainly caused by damage mechanisms as micro-cracking or plastic deformation due to the impact of steel balls. Such damage is supposed to increase with the increase of kinetic energy loss. According to Hutchings [32], kinetic energy loss is maximum at an impingement angle of 90°, where erosion rates are maximum for brittle materials. In the present study also, the peak erosion rate shifts to a larger value of impingement angle due to the brittle nature of carbon and glass fibres.

3.2. *Effect of exposure time*

Exposure time is defined, as it is a measure of accumulation of exposure to erosion or wear environment. Fig. 3(a) shows schematic representation of typical erosion diagram as a function of exposure time. In case of brittle erosion the weight loss increases linearly with time, in ductile erosion initially the particles may be embedded in the target surface causing weight gain. This period is generally known as incubation period. Once the incubation period has passed, wear usually proceeds at a constant rate. The maximum weight loss can be found at about 90 and 30° impingement angle for brittle and ductile erosion respectively (Fig. 3(b)).

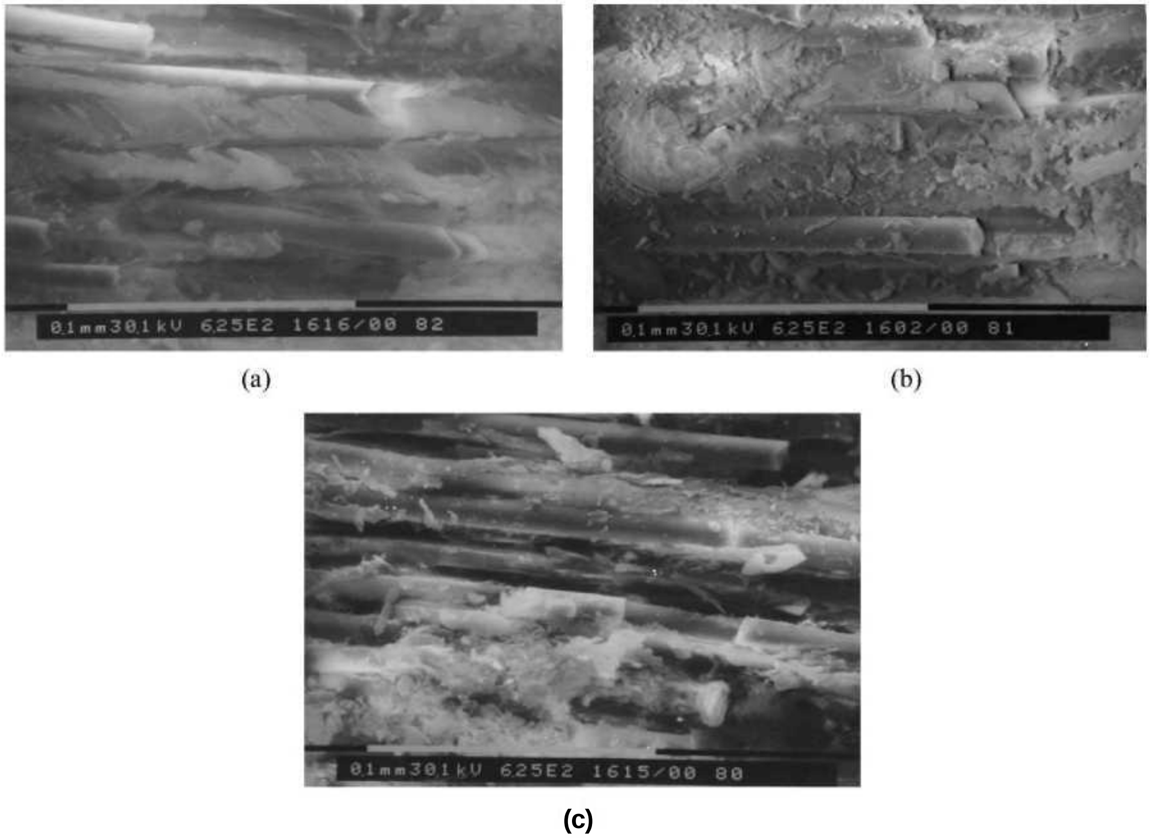


Fig. 9. SEM micrographs of GF/EP, composite eroded with steel balls of diameter = 300-500 mm; v = 45±5 m/s; exposure time= 180 s; impingement angle = 60° (a) 0° (b) 45° (c) 90° fibre orientations.

Fig. 5(a) and (b) show weight loss as a function of exposure time at different fibre orientations at impingement angle of 60°. The erosive wear increases linearly with exposure time for different fibre orientations in case of CF/EP, whereas in the case of GF/EP initially shown small incubation period, thereafter erosive wear increases linearly with time. Similar semi-ductile erosion behaviour has been observed in an E-glass-epoxy composite and has been attributed to good adhesion between matrix and the fibre [9]. Also, fibre orientation effect is not pronounced in case of GF/EP. 90/0 (0° fibre orientation) has shown maximum weight loss for both composites.

3.3. *Comparison of materials*

The comparison between CF/EP and GF/EP composites shows that erosive wear of GF/EP composite is higher than that of CF/EP composite for all the fibre orientations and different impingement angle (Fig. 4). Therefore, observed difference in erosion behaviour of these composites should be attributed to different fibre or interface properties. The comparisons of erosive wear performance at two different impingement angles (60 and 15°) for CF/EP, GF/EP is also shown in Fig. 6. The GF/EP composites have shown higher wear as compared to CF/EP composites. This may be due to the interface between matrix material and glass fibre that would be mechanically week. The analysis of experimental data presented above shows significant anisotropy of erosion behaviour of unidirectional reinforced composites under non-normal incidences. The other investigators [2,6] also observed anisotropy of erosion.

3.4. *Effect of fibre orientation*

The effect of fibre orientation on erosive wear of polymer composites has been studied to limited extent [2,6,10,11,19,20]. Earlier, investigators [2,6] observed anisotropy in the erosion behaviour of reinforced composites and pointed out the clear dependence of erosion rate on fibre orientations. In the present study carbon and glass fibre reinforced epoxy composites showed higher erosion in the 90/0 (0° fibre orientation) as compared to 90/45 (45° fibre orientation) and 90/90 (90° fibre orientation), especially at 60° impingement angle. These results are in agreement with some previous observations [2,6,11,19,20] but in disagreement with others [10]. It is well known that fibres in composites, subjected to particle flow, break in bending [2]. Fig. 7

shows a schematic diagram of erosive wear processes in unidirectional reinforced composites at different fibre orientations. In the case of an impact having a parallel component of the velocity with respect to the fibre orientation, bending requires particle indentation of the composites. Indention involves compressive stresses and the resistance to micro bending is very high. It is quite clear from the diagram that, under parallel impact, when the matrix material is removed, the steel balls hit the fibre directly and thus the interface between fibre and matrix becomes less dominant [Fig. 7(a)]. In case of perpendicular impact, the resistance to the lateral component of bending moment is lower and bundles of fibres get bent and broken more easily. This results in an increase in erosive wear [Fig. 7(b)]. Similarly in the case of 45° fibre orientation, the fibres are more prone to bend and break easily.

4. SEM studies

Figs. 8 and 9 show SEM micrographs of CF/EP, GF/EP composites eroded at 60° impingement angle where maximum wear was observed for different fibre orientations. SEM investigations revealed that erosion of CF/EP, GF/EP and in general thermoset composites is a complex process involving matrix micro cracking, fibre matrix debonding, fibre breakage and material removal [1,2,6,9]. The observed anisotropy of the erosion of these materials can be attributed to the following mechanisms.

It is well known that the fibres in composites, subjected to particle flow, break in bending [2]. In case of an impact having a parallel component of velocity with respect to the fibre orientation [Figs. 8(c) and 9(c)], bending requires particle indentation into the composite. The indentation involves compressive stresses and resistance to micro bending is very high. Thus there is local removal of resin material from the impacted surface; this results in the exposure of the fibres. For transverse particle impact [Figs. 8(a) and 9(a)], the resistance to lateral component of the bending moment is lower and bundles of fibres get bent and brake easily. This caused more erosive wear at 90/0 (0°- fibre orientation) in both composites. Also, in case of transverse erosion, high interfacial tensile stresses are generated by particle impacts. This causes intensive debonding and breakage of the fibres, which are not supported by the matrix. The continuous impact of steel balls on the fibres breaks the fibres because of the formation of cracks perpendicular to their length. The bending of fibres is possible because the surrounding matrix and supporting fibres have been removed [Fig. 8(a)]. A similar kind of observations was also made for 45° orientation (90/45) in both composites [Figs. 8(b) and 9(b)].

5. Conclusion

Based on the solid particle erosion studies of unidirectional CF/EP and GF/EP composites at various impingement angles and fibre orientations, the following conclusions are drawn:

1. The influence of impingement angle on erosive wear of both composites exhibited semi-ductile erosive wear behaviour with a maximum wear at a 60° impingement angle.
2. The fibre orientation has a significant influence on the erosive wear of composites. The erosion is higher when the steel balls impact on fibres normally than when they impact the composite in a direction parallel to the fibres. The degree of fibre breakage appears to vary with fibre orientation.
3. The comparison between CF/EP and GF/EP composite shows that the erosive wear of GF/EP composite is higher than that of CF/EP composite. Therefore, observed difference in erosive behaviour of these composites should be attributed to different fibre or interface properties.
4. SEM studies revealed that erosion is characterized by a multiple matrix microcracking and fibre matrix debonding.

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