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ORIGINAL ARTICLE

Erosion behaviour of epoxy based unidirectionl (GFRP) composite materials

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Abstract In the present work, the solid particle erosion behaviour and wear mechanism of commercial epoxy based unidirectional glass fibre reinforced plastics (GFRP) composites were investigated. The erosion experiments have been carried out using irregular silica sand (SiC) particles (150 ± 15 μm) as an erodent. The erosion losses of these composites were evaluated at various impingement angles (30°, 60° and 90°) with the change of both of erosion time and pressure. The erosion behaviour of (GFRP) has changed from ductile to brittle at 60° impingement angle and the erosion loss was the highest. The morphology of eroded surfaces was observed under scanning electron microscope and damage mechanisms were discussed.

1. Introduction

Polymer composites are extensively used as structural materials in various components and engineering parts in automobile, aerospace, marine and energetic applications due to their excellent specific properties. Polymer composites in pipe line carrying sand slurries in petroleum refining, helicopter rotor blades [1], pump impeller blades, high speed vehicles and aircraft operating in desert environments [2] are often exposed to conditions in which they may be subjected to solid particle erosion. The mechanical properties such as flexural strength can be degraded by the presence of localized impact damage after particle erosion [3]. It is also widely recognized that polymers and their composites have a poor erosion resistance against the operational requirements in dusty environment that might be overcome by understanding the characteristics of the polymeric composites. Consequently many researchers

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[4–6] have investigated the erosion behaviour of polymers and the composites worn by solid particles. There are some reports that discuss the particle erosion behaviour of continuous fiber laminated composites. However, these mainly discussed the erosion behaviour and the performances, although, various types of laminates were used for reinforcing plastics [7,8]. After developing primitive fiber reinforced plastics (FRP) in 1940's they have been widely used because of their superior specific strength and also high corrosion resistance. Initially FRP was composite reinforced with glass fibers (GFRP), however, reinforcement by new fibers such as carbon/graphite and aramid have increased their importance recently. Following the development of these high-performance fibers, use of FRP into industrial applications such as load bearing parts of buildings, bridges, tank/vessels and transportation can be recognized .To ensure the durability of FRPs for industrial applications, it is necessary to discuss the degradation behaviour and mechanism under various conditions such as stress, corrosion and erosion, etc. Several parts and equipments are exposed to erosive conditions, for example, pipes for hydraulic or pneumatic transportation, nozzle and impeller for sand-blasting facility, internal surface of vessels used for fluidized bed or with catalysis, nose of high-velocity vehicle, blades/propellers of planes and helicopters, etc. Some of them are made from fibrous composites [9]. In this study, we focus on the sand erosion damage of fibrous composites. There are several reports in the literature which discuss the erosion behaviour of fibrous composites. These papers mainly showed, however, only the erosion behaviour and the performances to erosive damage [10–13]. Although various types of fiber are used for reinforcing plastics, no paper in which the effect of types of fiber, e.g., strand mat, woven cloth, unidirectional UD fiber, etc. on sand ero-

Table 1 Composite material testing standards.

Test type	Standard
Tension	EN ISO 527-5 1997 ANSI/ASTM D3039/D3039M-00 ASTM D638-01 2001
Compression	BS EN ISO 14126:1999 ASTM D3410/D3410M-95 1995
Shear	ASTM D5379/D5378M-98 1998

Table 2 Mechanical properties of GFRP samples used in the erosion tests.

Property	GFRP	GFRP Ref. [20]	GFRP design manual [21]
E_{11} (GPa)	22.8	20.7	17.2
Tension (compression)	(22.5)	(20.2)	(17.2)
E_{22} (GPa)	8.9	–	5.516
Tension (compression)	(–)	(–)	(6.90)
Poisson's ratio v_{12}	0.3	0.32	–
Tension (compression)	(–)	(0.33)	
Ultimate strength (MPa)	255	265	207
Tension (compression)	(265)	(267)	(104)
G_{12} (GPa)	3.41	3.75	–
Ultimate shear strength (MPa)	78	85.9	–

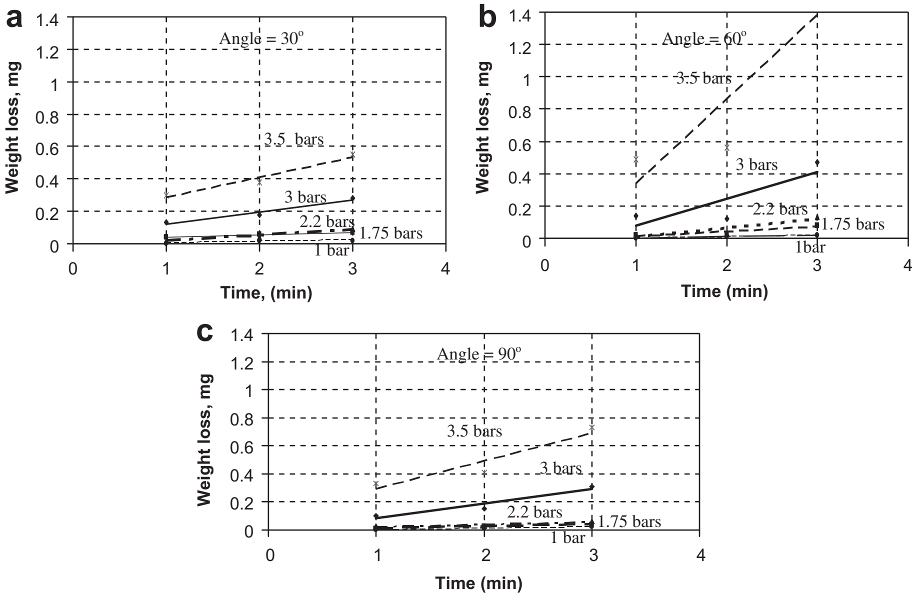

Figure 1 Weight loss of GFRP composite as a function of erosion time at different pressures (a) 30° (b) 60° and (c) 90°.

sion damage has been published discussed systematically. The aim of present study was to evaluate the solid particle erosion behaviour of unidirectional glass fiber reinforced plastics (GFRP) composites under different impact conditions using irregular silica sand particles as an erodent.

2. Experimental work

2.1. Materials

The material used in the current work is a commercial unidirectional GFRP composite material. The plates used in making the test samples are made by Extren® [14]. The mechanical properties of the material are evaluated using standard test procedures listed in Table 1 for tension, compression and shear properties. Tests were carried out using standard testing machines. Details of the tests procedures, specimen preparation and analysis are presented in [15,16]. Tests results are compared with the manufacturer manual for material data and summarized in Table 2.

2.2. Erosion testing

Before the erosive wear tests all specimens were cleaned with acetone, weighed at electronic balance with sensitivity of 0.01 mg. Great care was given to ensure clean surface before and after wear tests. Sand and dust particles were cleaned after erosion test with air blasting and then balanced carefully. The room temperature erosion test facility has been used, in the present investigation, with irregular silica sand particles with the size of 150 ± 15 μm which were driven by a static pressure, of (1–3.5 bar) Composite samples of approximately $40 \times 40 \times 2$ mm in dimensions are mounted in the specimen holder. Then the mounted specimens were subjected to a particle flow at a given impingement angles between 30° and 90° to the specimen surface which placed horizontally. Wear was measured by weight loss after 1, 2 and 3 min of erosion. To charac-

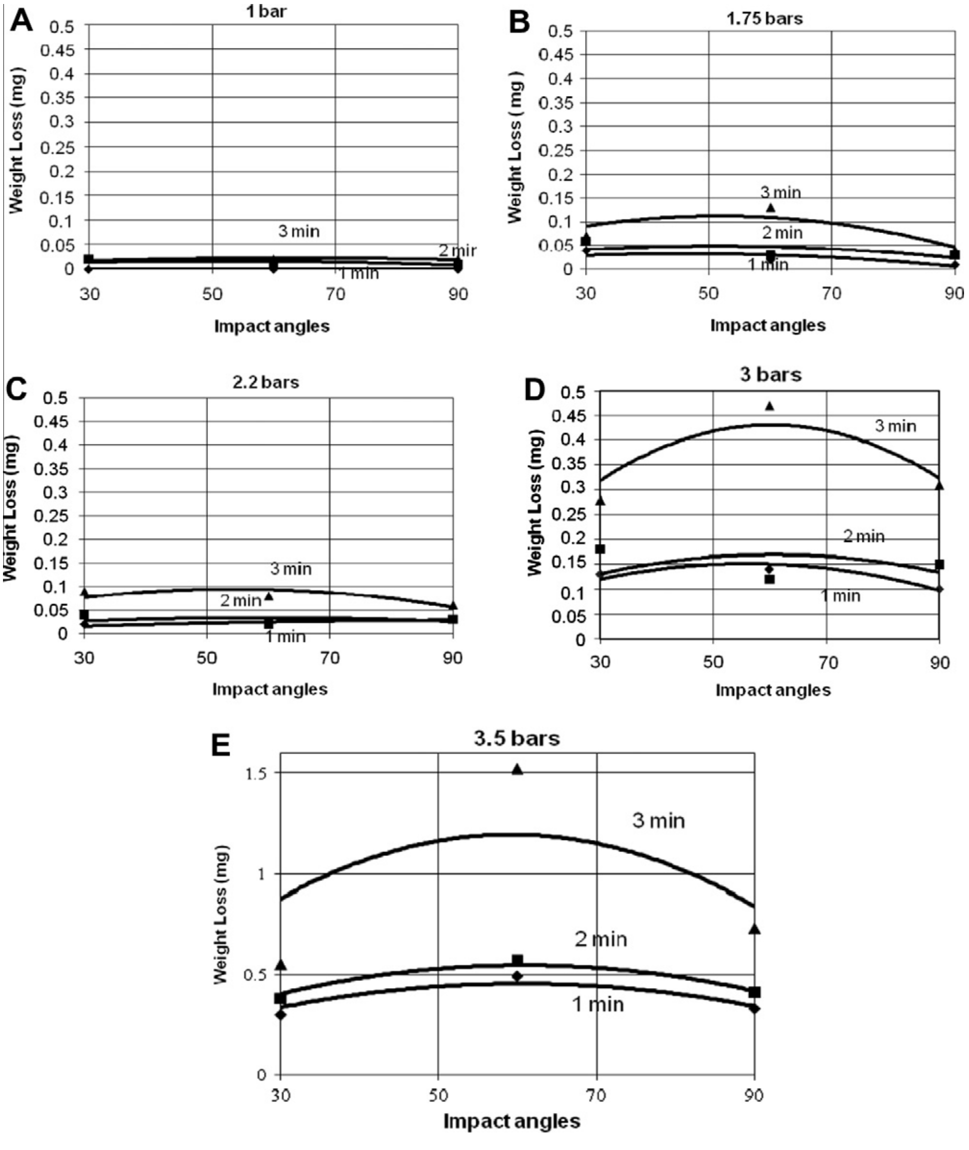

Figure 2 The erosion loss at an impingement angles at different erosion time for different pressures.

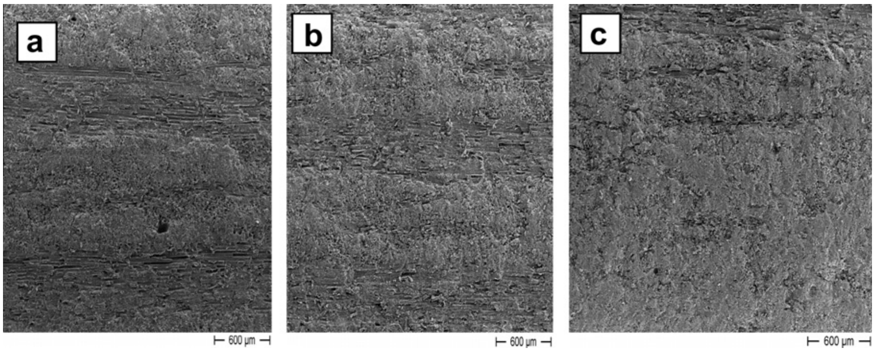

Figure 3 SEM for surface of erosion (a) 1.75 bar, 3 min, and 30° (b) 1.75 bar, 3 min, and 60° and (c) 1.75 bar, 3 min, and 90° conditions.

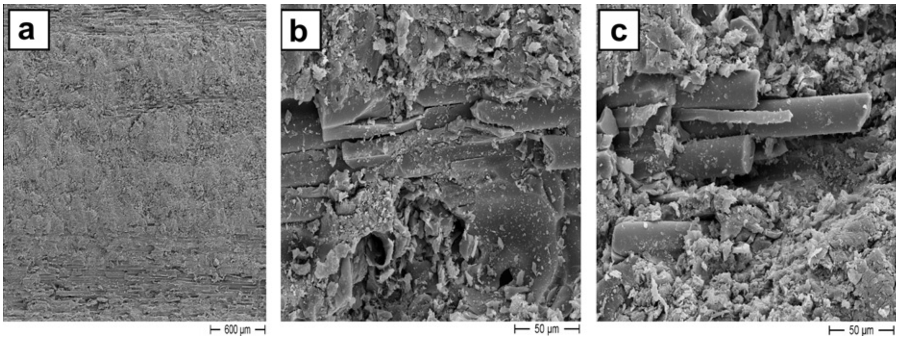

Figure 4 SEM for surface of erosion at (a) 3 bar, 3 min, 30° (b) 3 bar, 3 min, 60° and (c) 3 bar, 3 min, and 90° conditions.

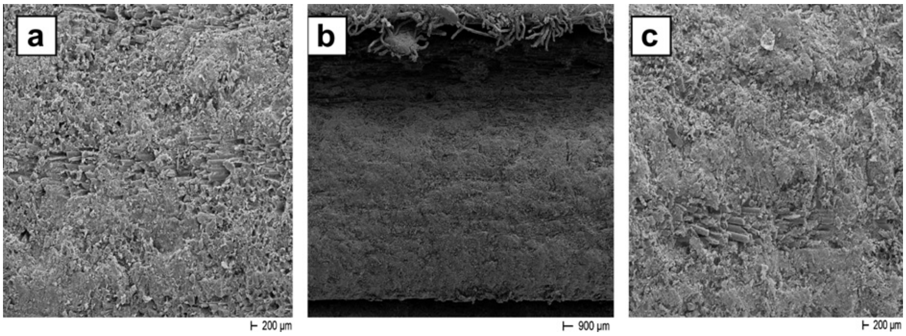

Figure 5 SEM for surface of erosion at (a) 3.5 bar, 3 min, and 30° (b) 3.5 bar, 3 min, and 60° and (c) 3.5 bar, 3 min, and 90° conditions.

terize the morphology of the eroded surfaces and to understand the mechanism of material removal, the eroded samples were observed using a scanning electron microscope (SEM).

3. Results and discussion

Fig. 1 shows the erosive wear behaviour of the glass-fibre reinforced, polymer matrix composites (GFRP) with different pressures at various erosion times. The weight loss of GFRP composite is presented in Fig. 1 as a function of erosion time, and pressure at different impingement angles. The curves show that the weight loss of the test samples is proportional to the erosion time for each pressure (1, 1.75, 2.2, 3, and 3.5 bar) and impingement angle (30°, 60° and 90°) that has impacted on the specimen in the form of brittle materials [17].

Fig. 2 shows the variation of the erosion rates as a function of impingement angles for different erosion times and pressures. The test results shown in Fig. 2 indicate that, the wear rate increases with increasing impingement angle to a certain angle and then it starts to decrease again. The influence of the impact pressure is obvious and it can be seen that the increase of the impact pressure dramatically increases the weight loss. For example the weight loss increases eight times when increasing the pressure from 1 bar to 3.5 bar for 1 min exposure time and at an impingement angle of 60°. Another factor having a significant effect on the weigh loss which is the exposure time which is obvious for this kind of wear mechanism. The weight loss increases dramatically with the exposure time especially for high pressures, e.g., 3 and 3.5 bar and an angle of 60°. It is well known that, the impingement angle has a great influence on the particle erosion. Other parameters such as hardness of the erodent particles and particle velocity should be considered. The combined effect of impact pressure and impingement angle of the particles is clearly indicated in Fig. 2E, in which the erosion rate (weight loss) is the highest at impingement angle of 60° and the erosion rate is significantly affected by the increase in impact pressure. For example, at an impingement angle of 60°, the highest erosion rate was at 3.5 bars which is higher than the other pressures as illustrated in Fig. 2A–E.

This conclusion is supported by the morphology of the samples shown in Figs. 4 and 5 as it is going to be discussed in the next section. This result agrees with those obtained by [18,19] for other composite materials and it represents the evidence of the semi-ductile nature of (GFRP) composite materials. The effects of high pressure and high impingement angle of the particles (90°) are observed in Figs. 4c and 5c. Also remarkable matrix deformations and removals are seen in Figs. 3–5. The fractured small fibre fragments randomly distributed in the roughly deformed matrix and loss their original directions. Remarkable high fibre/matrix interfacial deformations occurred. Particles transferred all their kinetic energies to the material surface. This energy is spent for fibre cracking, fibre/matrix interfacial deformations, matrix deformation and matrix removals [14].The erosion of fibre is mainly caused by damage mechanisms as micro-cracking or plastic deformation due to the impact of silica sand. Such damage is supposed to increase with the increase of kinetic energy loss. Kinetic energy loss is maximum at an impingement angle of 90°, where erosion rates are maximum for brittle materials [20]. In general, thermoplastic matrix composites exhibit a ductile erosive wear (plastic deformation, ploughing, and ductile tearing), while thermosetting matrix composites erode in a brittle manner (generation and propagation of surface lateral cracks). However, this failure classification is not definitive because the erosion behaviour of composites depends strongly on the experimental conditions and the composition of the target material. It is well known that impingement angle is one of the most important parameters in erosion behaviour. When the erosive particles hit the target at low angles, the impact force can be divided into two components: one parallel (Fp) to the surface of the material and the other vertical (Fv). Fp controls the abrasive and Fv is responsible for the impact phenomenon. As the impact angle shifts towards 90°, the effects of Fv become marginal. It is obvious that in the case of normal erosion all available energy is dissipated by impact and micro cracking, while at oblique angles due to the decisive role of the Fv the damage occurs by micro-cutting and micro-ploughing [21]. Fig. 3 shows the micrographs of surfaces eroded at an impingement angle of 30°, 60° and 90°. When impacting at low angles, the hard erodent particles can penetrate the surfaces of the samples and cause material removal by micro-cutting and micro-ploughing.

It is possible to investigate the particle flow direction easily from the wear trace of the particles, which are indicated by arrows in the micrographs as shown in Figs. 3a, 4a and 5a. As explained above in lower impingement angles, erosive wear happened dominantly in abrasive mode. The higher particle pressure of 3.5 bar (Fig. 5a) makes the sample surface remarkably rougher compared to the lower particle pressure of 3 bar (Fig. 4a) at the same impingement angle 30°.

4. Conclusions

Based on this study of the solid particle erosion of unidirectional GFRP at various impingement angles and impact pressures, the following conclusions can be concluded:

(1) GFRP material exhibited a maximum erosion rate (weight loss) at an impingement angle of 60° under the present experimental condition for different pressures and erosion times.
(2) The material wear mechanisms are in close relationship with the impingement angles.
(3) The morphologies of eroded surfaces observed by SEM suggest that the overall erosion damage of composites consists of matrix removal and exposure of fibres, fibre cracking and removal of broken fibres.

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