Solid Particle Erosion of Unidirectional GF Reinforced EP Composites with Different Fiber/Matrix Adhesion

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ABSTRACT: The influence of interfacial modification and relative fiber orientation (parallel, Pa and perpendicular, Pe) on the solid particle erosion was investigated in unidirectional (UD) reinforced glass fiber (GF) epoxy (EP) composites. The interfacial modification was varied by GF sizing. The erosive wear behavior was studied in a modified sandblasting apparatus at three impact angles (30, 60 and 90°). The surface topography of the eroded composites was investigated by a scanning electron microscope (SEM) and a non-contact 3D laser profilometer.

The results showed a strong dependence of the erosive wear on the jet angle. The GF/EP systems presented a brittle erosion behavior, with maximum weight loss at 90° impact angle. It was established that good fiber/matrix adhesion improved the resistance to erosive wear. On the other hand, the relative fiber orientation had a negligible effect except the erosion at 30° impact angle. High roughness of the eroded surfaces indicated for high erosion rates, i.e. low resistance to solid particle erosion.

KEY WORDS: fiber–matrix interface, jet-erosion, impact angle, fiber orientation, GF/EP composites.

INTRODUCTION

NOWADAYS POLYMERIC COMPOSITE materials are extensively used in engineering applications due to their excellent specific (i.e. density related) properties. They also find applications in fields where high

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resistance to wear, abrasion and erosion is required (automobile, aerospace, marine, mining, energetic etc) [1–3]. Until now, however, the interest was concentrated on the erosion behavior of traditional materials. It was reported that polymer composite materials exhibit poor erosion resistance [1–10]. Therefore, the improvement of their resistance to erosive wear is of substantial interest. The influence of various factors, such as erodent flux conditions, erosive particle characteristics and target material properties has been also studied [11]. However, limited information is available on the effect of fiber/matrix adhesion on the erosion of fiber reinforced plastics [1,4,8]. Further, the mechanisms of erosion and how inherent properties of the composites, such as interfacial shear strength, affect the erosion behavior are less understood. Miyazaki et al. studied the effect of fiber/matrix interface strength on the erosion behavior of unsaturated polyester (UP) and epoxy resins (EP) reinforced by treated and untreated glass (GF) [4] and carbon fibers (CF) [8], respectively. For the latter system no difference in the interfacial strength resulting from the fiber surface treatment was observed and thus its effect on the erosion rate could not be deduced. Our intention was therefore to investigate the solid particle erosion characteristics of unidirectional (UD) GF reinforced EP composites and to elucidate the effect of interfacial modification on their erosion wear. A further aim of this study was to investigate how the relative fiber orientation influences the erosive wear behavior.

EXPERIMENTAL

Materials

Table 1 lists the composition and designation of the materials tested. In the present study, three systems, viz. two composites reinforced by differently sized GF, respectively in addition to the pure EP resin were investigated.

Table 1. Composition, designation and interfacial shear strength values of the composites tested.

Designation	Fiber Volume Content (V_f) [%]	Sizing	Average Fiber Diameter [μm]	Interfacial shear strength (τ_i) [MPa]
EP	0	–	–	–
GF/EP	68	PP compatible	17	32
GF/EP-M	68	EP compatible	17	56

A hot-curing epoxy system (bisphenol-A-based resin Araldit LY 556; anhydride hardener HY 917, 90 phr; heterocyclic amine catalyst DY 070, 1 phr; all from Ciba, Basel, Switzerland) was selected. The GF (diameter: 17 μm) provided by PPG Industry Fiber Glass (Hoogezand, the Netherlands) varied only in their sizing. Either an EP-compatible sizing (GF/EP-M), or an incompatible (having a polypropylene compatible sizing; GF/EP) one was applied on GF. UD laminates were produced by wet filament winding of the GF rovings on a flat aluminum plate. Their consolidation occurred in an autoclave curing cycle: 4 h/80°C + 8 h/120°C with subsequent cooling. The mean fiber volume fraction (V_f) of the GF/EP composites was of about 0.68 ± 0.02 established by ashing the material.

Testing

The interfacial shear strength of the above mentioned materials was determined by the single fiber micro-droplet pull-off technique. The way of preparation of the single-fiber model specimens and the testing procedure are similar to that described in earlier studies [12,13]. The embedded fiber length was in a range between 60 and 160 μm. Load–displacement curves were monitored on an *x–y* plotter. Interfacial failure occurred when the applied force reached the maximum value $F_{\max}$ and dropped subsequently. The calculation of the interfacial shear strength (τ_i) values was obtained by the following expression:

$$\tau_i = \frac{F_{\max}}{\pi D L} \tag{1}$$

where $F_{\max}$ is the maximum tensile load and D and L, the fiber diameter and embedded fiber length (determined by scanning electron microscope (SEM)), respectively. It was assumed that uniform shear yielding occurred during the test [12,13].

All the erosion tests were performed in a sand-blasting chamber (Figure 1) by sharp, angular corundum with a particle size between 60 and 120 μm. The distance between the sample holder and the nozzle was constant (220 mm). The impact angle was adjusted by tilting the sample holder (Figure 1). Three impingement angles were selected (30, 60 and 90°). Though the speed of the erodent particles can be varied by modifying the air pressure in the nozzle, it was kept constant at 6 bar. This corresponds to a jet speed of ca. 70 m/s according to a rotating double slot disk calibration method [14]. All erosion tests were performed at room temperature. The eroded area was also constant as a steel cover frame with a circular opening was placed on the surface of the specimens.

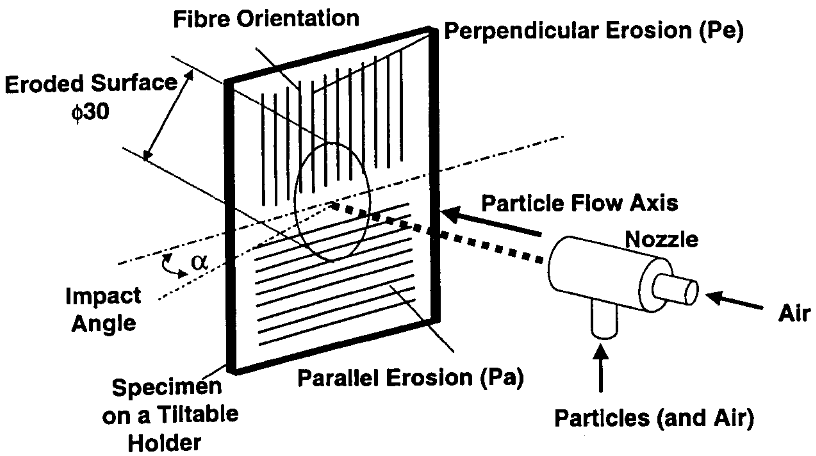


Figure 1. *Test set-up to study the solid particle erosion of UD fiber reinforced composites schematically.*

The composite weight loss was recorded as a function of erosion time by a precision balance (AT261 Mettler Toledo, sensibility 50 μg). Before weighing, the corundum particles were removed from the specimen surface by air blasting. Figure 1 illustrates the parallel (Pa) and perpendicular (Pe) orientation of GF relative to the erosion direction for the UD composites.

The eroded surface was inspected in a Jeol SEM (Tokyo, Japan) . The samples were gold-sputtered in order to reduce charging of the surface. The surface morphology of the eroded samples was also examined in a laser profilometer of UBM Messtechnik GmbH (Ettlingen, Germany). This system is facilitated with an opto-electronic 3D table for contactless measurement of the surface roughness profile (according to DIN4768 and DIN4776 standards). The scanned area was a rectangular part of the eroded surface with dimensions of 2.8 by 2.8 mm.

RESULTS AND DISCUSSION

Interfacial Shear Strength (IFSS)

The τ_i value obtained from the microdroplet pull-off tests was 32 MPa for the poorly (GF/EP) and 56 MPa for the well-bonded composite (GF/EP-M), respectively (Table 1). This difference confirms that a suitable GF sizing may led to a significant improvement of the interfacial shear strength of the composite (improvement 75%).

Erosive Wear Behavior (Steady State Erosion)

Figure 2 shows typical erosion diagrams as a function of impact time and angle, respectively. The jet-erosion mechanisms can be grouped in ductile and brittle categories. Whereas in brittle erosion the weight loss increases linearly with time, in a ductile type initially the particles may be embedded in the target surface causing a weight gain. This period is denoted as incubation period. By further bombardment, however, a linear weight loss as a function of time is observed usually. The maximum weight loss can be found at about 90 and 30° impact angles for brittle and ductile erosions, respectively.

Note that this grouping is not definitive [9]. Hutchings [15] observed that a material can show either a ductile or a brittle behavior by changing in the erosion conditions, such as impact velocity or angle, particle flux, abrasive particle properties (shape, hardness or size) etc. As a consequence, the above failure classification is often disputed in the literature. Häger et al. [1] made erosion tests on samples of GF/EP, CF/EP, CF-reinforced polyetherether-ketone (CF/PEEK), CF-reinforced polyetherketoneketone (CF/PEKK) and aramid fiber-reinforced EP (AF/EP). The authors claimed a semi-ductile behavior for both thermoset and thermoplastic composites under jet-erosion by 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. [6] came to similar conclusions in the case of E-glass/EP composites. The erodent medium in the latter study was natural sand between 210 and 297 μm size. A different observation was made by Tsiang [9], who used aluminum oxide particles and garnet sand as abrasives. In this study, the author concluded that in GF/EP, as well as in all other composites with thermoset matrices, the erosion occurred brittlely, while in composites with thermoplastic matrices a semi-ductile erosion was dominant. The study of Roy et al. [10] corroborated that thermosetting matrix composites are eroded in a brittle manner, whereas thermoplastic matrix based composites

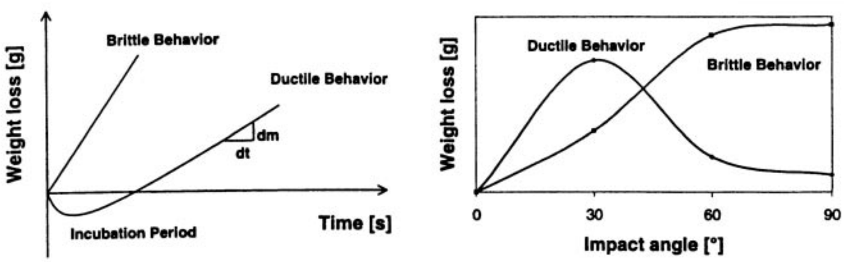


Figure 2. *Schematic diagram of brittle and ductile type erosive wear.*

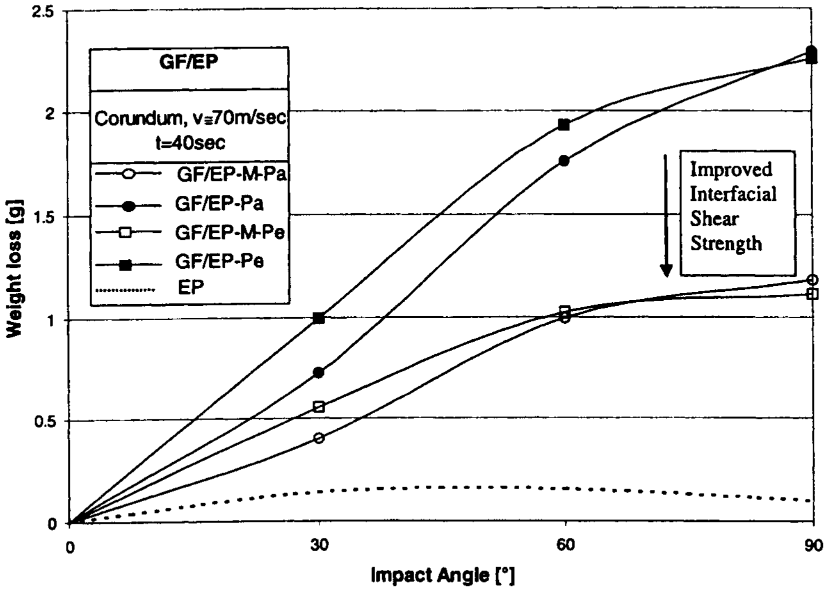


Figure 3. Influence of impact angle, erosion direction and interface modification on the erosive wear of EP and GF/EP composites.

fail in a ductile manner. This statement was made after a study of GF reinforced polymer composites eroded by silica sand.

Figure 3 displays the influence of the impact angle on the erosive wear of the GF/EP systems tested in this study. One can recognize that the GF/EP composites undergo brittle type erosion irrespective of the fiber orientation and interfacial modification. All GF/EP composites showed a linear increase of weight loss with impact time from the beginning of the experiments. The maximum weight loss was found at 90° impact angle. This behavior suggests that the temperature rise due to solid particle impact likely did not pass the glass transition (T_g) of the EP resin, therefore a brittle erosion is favored [5]. Otherwise, the related thermal softening should result in semi-ductile or ductile failure mode.

From Figure 3, it is also evident that the sizing of GF had a pronounced effect on the erosive wear of GF/EP. The composites with EP-compatible GF presented a much higher erosion resistance compared to the EP-incompatible sized GF containing composites, for all impact angles. The difference in the interfacial adhesion is best reflected at 90° impact angle, when the weight loss due to erosion reaches its maximum. Accordingly, the adhesion promoted by proper fiber sizing strongly improved the erosion resistance of GF/EP composites. This indicates that the interface between matrix and fiber plays an important role with respect to solid particle erosion.

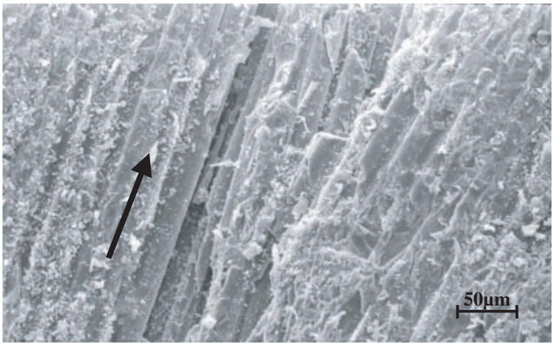
The effect of fiber orientation on the weight loss can also be deduced from Figure 3. There is no sense in indicating the erosion direction in the case of 90° impact because the particles hit the same transverse area. The GF/EP composites showed a higher weight loss in Pe- than in Pa-direction, especially at 30° angle. These results are in agreement with some previous observations [1,8] but are in contrast with others [9]. In order to compare our results with the preliminary published ones, the surface topography was inspected by SEM and non-contact 3D laser profilometry.

Surface Topography and Erosion Mechanisms

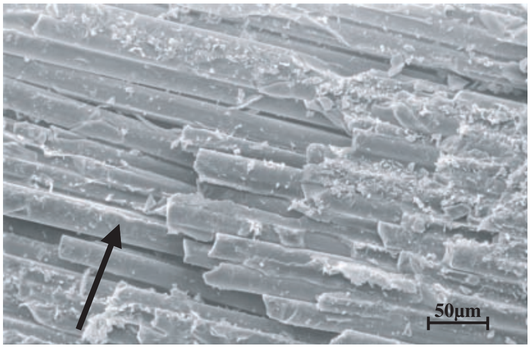
The surface of the GF/EP composites was examined by SEM and laser profilometer before and after the erosion tests. The surface contours and their change are very informative with respect to the internal (interfacial modification) and external conditions (impact angle and impact direction), respectively. Next the most important results will be surveyed briefly.

Figure 4 illustrates the effect of relative fiber orientation on the erosion wear of GF/EP. The failure mode in GF/EP and in general in thermoset composites is a complex process involving matrix micro-cracking, fiber/matrix debonding, fiber breakage and material removal [1,5,6]. The main reason for the fiber fracture is bending. In Pa-direction hardly any bending occurs in contrast to the Pe case. This becomes obvious in Figure 4. In Pe case, broken fibers along with multiple matrix cracking can be resolved (Figure 4b), while in case of Pa-direction less resin is removed and there is no sign of fiber breakage (Figure 4a). The above difference was very clear for the unmodified system, especially at a 30° impact angle (Figure 4). There was, however, a smaller difference between the Pa- and Pe-directions of impact for the GF/EP-M system. This suggests, that improved fiber/matrix adhesion is associated with a higher resistance to erosive wear even under the most severe Pe condition.

Figure 5 gives a scheme on the role of interface in the erosion of UD-reinforced composites. Clearly seen that under Pa impact, when the matrix material is removed, the abrasive material hits directly the fiber and thus the interface between fiber and matrix becomes less dominant. By contrast, under Pe impact the abrasive material erodes the matrix between the fibers, fractures the fibers and removes their fragments. Low interfacial shear stress between GF and EP facilitates the debonding and breakage of fibers which are not supported by the matrix. These fibers are then easily removed. Good bonding between GF and EP however, resulted in a better erosion resistance as the fiber bending due to impact is substantially reduced. As a



(a)



(b)

Figure 4. *SEM micrographs taken on the eroded surface of composites impacted at 30° angle for 40s Designation: (a) GF/EP-Pa and (b) GF/EP-Pe.*

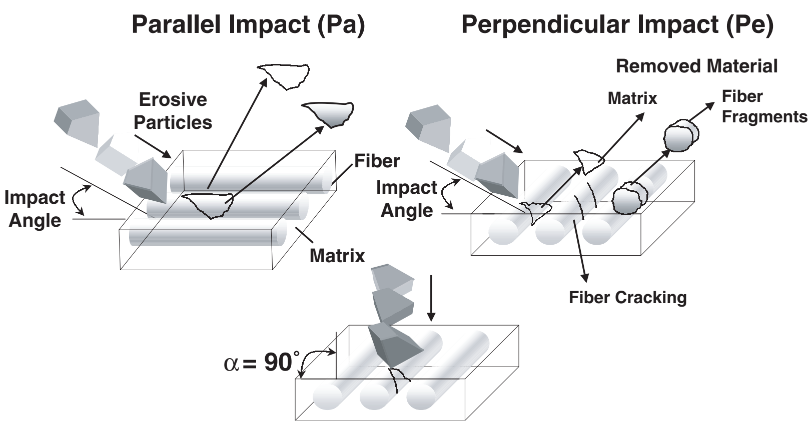
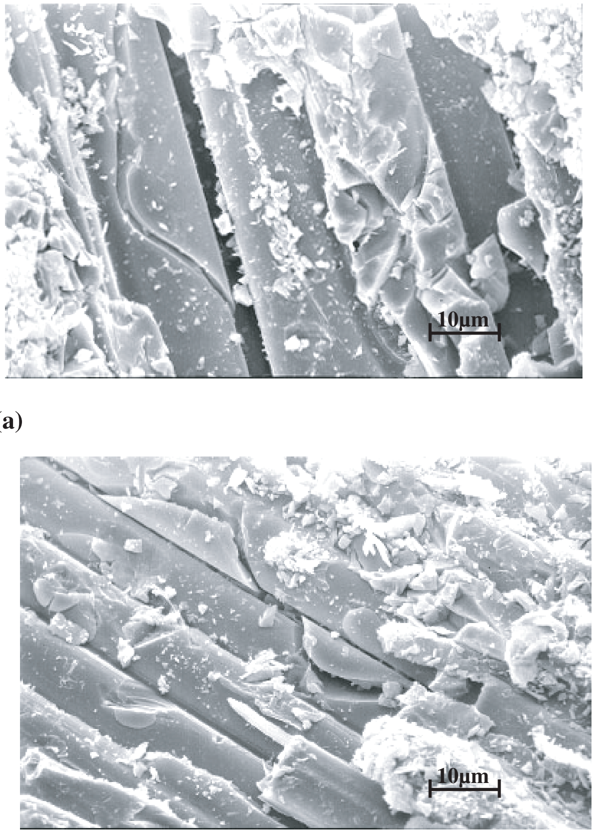


Figure 5. *Scheme of the role of the interface on the erosion of UD fiber-reinforced composites under parallel (Pa) and perpendicular (Pe) impact conditions.*



(a)

(b)

Figure 6. *SEM micrographs of GF/EP composites impacted at 90° angle for 40 s with (a) good and (b) poor fiber/matrix adhesion: Designation (a) GF/EP-M and (b) GF/EP.*

consequence, the modified systems present only a small difference between Pa and Pe impact directions during solid particle erosion.

The role of interfacial modification is further illustrated in Figure 6 for the case of GF/EP systems eroded at 90° impact angle. In case of unmodified systems (Figure 6b) the matrix shows multiple fracture and material removal. The exposed fibers are broken into fragments and thus can be easily removed from the worn surface. This is not the case for modified systems, where the fiber fragments are well bonded to the matrix and thus kept for longer time on the eroded surface (Figure 6a). All these observations, based on SEM micrographs, are in line with those made in earlier studies [5,9].

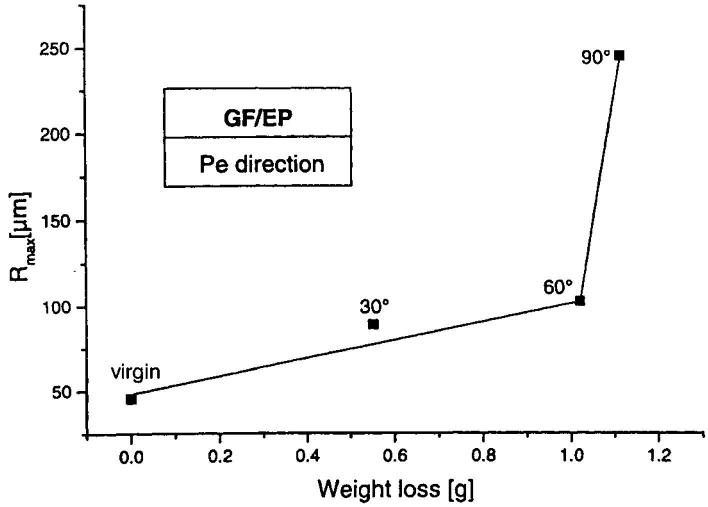


Figure 7. *Change of the roughness parameter R_{max} as a function of impact angle for GF/EP-M tested in Pe direction.*

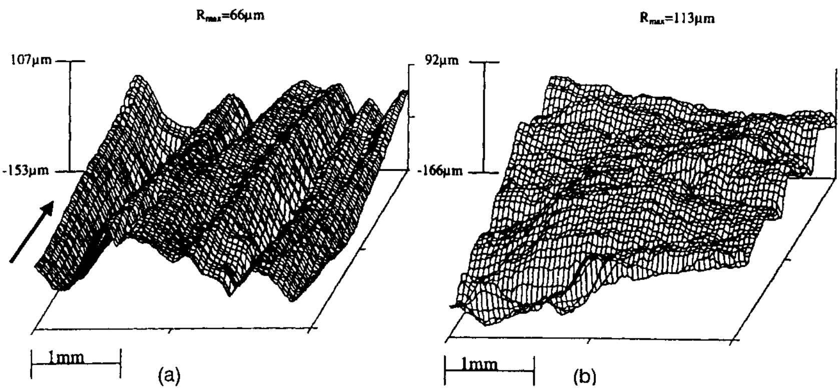


Figure 8. *3D roughness contour of GF/EP composite eroded in Pa direction for 40 s Designation: (a) 30° and (b) 90°. Note: this figure shows that brittle erosion occurred and that R_{max} changes parallel with the erosion rate.*

The last part of this study is an attempt to investigate the surface topography through a laser-profilometer system and to correlate the roughness parameters with the wear behavior of the composites tested. The maximum roughness depth (R_{max}, according to DIN4776) was selected as characteristic parameter. The variation of R_{max} with the impact angle for GF/EP was also considered. As expected, R_{max} changed parallel with the weight loss (Figure 3). Figure 7 illustrates this variation for GF/EP-M-Pe, and confirms the above mentioned correlation: where the weight loss is high, the roughness parameter also is high. Figure 7 also shows the impact angle dependence which confirms the brittle erosion occurred.

Figure 8 presents the 3D contours from the scanned area of the eroded surfaces of GF/EP-M, at 30 and 90° impact angles, respectively. These contour plots substantiate the conclusion made from SEM observations, viz. that GF/EP exhibits the maximum erosion rate at 90° impact angle. In addition, Figure 8 shows the above mentioned correlation between erosion rate and roughness parameters.

CONCLUSIONS

Based on this study performed on the solid particle erosion of unidirectional GF/EP composites of various interface properties at various impact angles and relative fiber alignment, the following conclusions can be drawn:

- The erosive wear is a function of impact angle for both EP and GF/EP composites. The maximum weight loss due to erosion is found at 90° (transverse) impact angle.
- An improvement in the interfacial shear strength via GF sizing strongly improves the resistance to erosive wear. The impact direction has a negligible influence on the erosive wear of GF/EP composites with good adhesion between matrix and fibers.
- The roughness of the eroded surface correlates with the weight loss due to erosion.

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