Experimental study of temperature erosion tests on bidirectional coated and uncoated composites materials

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Abstract
In this research work, temperature erosion wear tests, on composites materials (carbon fiber and glass fiber), were carried out. The tests were made on uncoated and coated materials using a polyester resin (Gelcoat), which is used to protect the leading edge of wind turbine blades against the weather and UV rays and is of interest, in this study, to know the behaviour of this coating subjected to hard particles erosion. The tests were performed at 50 °C, in order to simulate de extreme temperature in the coast of Oaxaca, Mexico, where some wind turbines are installed using blades made of fiberglass coated with gelcoat. Erosion tests were performed in a platform that was developed from the ASTM G76 standard. The rectangular samples had 25 × 18 mm and thickness of 4 mm. Sea sand from coast of Oaxaca was utilized as erosive particle. Three different impact angles were used 75°, 85° and 90°. The particle velocity was adjusted at 12 m s⁻¹. To determine the mass loss, the samples were weighed before the test and reweighed every 2 min to measure the amount of mass loss until complete the 6 min of the test. In order to identify the wear mechanisms, Scanning Electron Microscopy was used. The average roughness (Ra) and profiles of the samples tested were determined with a 3D optical profiometer. The results showed that Carbon fiber composite material had 3 times more resistance to erosive wear than fiberglass.

1. Introduction
The topic of erosion in composite materials has received significant attention in recent years. The interest in this area is proportional to the growing use of composite materials in the aeronautical and wind industry, where durability is a primary consideration [1, 2]. It was found that the erosion behaviour of the epoxy compounds is controlled by the type of fiber, the composition, the shape of the particles and the angle of impact [3–5]. Suresh et al found that the orientation of the fiber has a significant influence on the erosion rate at low impact angles and the erosion rate, on composite materials, is higher when the particles impact perpendicularly than in parallel to the direction of the fiber [6, 7]. In the study realized by Valaker it was observed that the roughness of a surface is a very important parameter in the erosion by solid particles [8]. Fouad observed that the erosion in composite materials begins with crack formation, matrix removal and fiber exposure [9]. In other study, it was found that the variation of impact velocity has a greater effect on erosion wear rate than erosive particle size variation [10]. Antil et al studied the erosion behaviour of SiC/glass fiber reinforced epoxy composites using river sand, beach sand and desert sand as erodent particle. It was found that the maximum damage was obtained with river sand particles [11] and that the erosion behavior showed that the reinforcement size affects, predominantly, the resistance to erosion [12]. The use of wet sand particle to study the erosion on carbon steel and HDPE at impact
angles of 30°, 90°, and −30°, revealed that carbon steel had a significant erosion, particularly at 90° [13]. In the same way, wet sand fine particles were used to study the erosion on mild steel plate in two-phase flow at different collision angles [14]. In other work made by Malipatil [15], solid particle erosion of PMC’s carbon/vinylester was studied. The experimental showed that impingement velocity had the greatest influence on the erosion rate followed by impact angle. In the other hand some studies of finite element models have been developed to predict the erosion behaviour of unidirectional epoxy carbon fiber composites subjected to impact of solid particles [16]. In the wind industry, complex engineering challenges are revealed; one of them is the erosion in the leading edge of wind turbine blades [17]. The effects of sand particle size on the performance characteristics of a vertical axis wind turbine revealed that particles smaller than 100 μm adhere to the surface at the moment of impact; for larger particles the probability of adhesion depends on particle size, impact velocity and temperature, in addition to unpredictable and potentially volatile operating environmental conditions [18]. Carbon fibers are recommended as a promising solution for the manufacture of wind turbine blades as they have greater rigidity and better mechanical properties [19]. Erosion at the leading edge is an emerging problem in the reliability of wind turbine blades, which causes a decrease in performance and additional maintenance costs. Particularly, in onshore wind turbines installed in Coast of Oaxaca, Mexico, the erosion by solid particles, sea sand mainly, is a great problem. The objective of this research is to conduct a study of erosion at a controlled temperature of 50 °C using sea sand as an erosive particle on fiberglass and carbon fiber composite materials, without and with Gelcoat coating, in order to simulate the climate that mainly takes place at the leading edge of wind turbine blades installed in maritime areas of Mexico, where climate can reaches this temperature.

2. Experimental

2.1. Materials
Fiberglass and carbon fiber composite materials were manufactured from the Resin Transfer Molding (RTM) process [20, 21]. The process consists of injecting an epoxy resin Epolam 2015 with hardener into a closed aluminium mold. For each 100 g of resin, 32 g of Epolam hardener were mixed. Then the mold was placed in a hot plate hydraulic press, where a load of 1.5 tons was applied. This compresses the layers of fibers to later make the injection of resin. The injection was made at 17 cc min⁻¹ and 50 °C, using a positive injection pressure of 70 psi for 120 min. The total curing time was 4.5 h at 60 °C. After the curing time, the laminates were removed from the mold. Figures 1(a) and (b) show the glass fiber and carbon fiber fabrics, respectively, used with bidirectional fabric at 0/90°.

Once the fiberglass and carbon fiber sheets were obtained by RTM, samples were cut to obtain rectangular shapes of 25 mm × 18 mm and 4 mm thickness. A polyester resin (Gelcoat) was applied to some samples in order to compare the erosion wear resistance in coated and uncoated materials. Gelcoat was applied with a curing brush at room temperature. The average thickness of coating was 0.55 mm (figure 2). The gelcoat generally is used to protect the surface of wind turbine blades against the weather and UV rays and was of interest to know the behaviour of this coating subjected to hard particles erosion. To carry out the erosion tests, particles of sea sand were used, which were collected on the coast of Oaxaca, Mexico, where some onshore wind turbines are installed.

2.2. Test procedure
Temperature erosion tests were performed in a platform that was developed from the ASTM G76 standard [22]. A schematic diagram and an image of the platform are shown in figures 3(a) and (b), respectively. A nozzle of 4.7 mm internal diameter and 6.3 mm external diameter with a length of 260 mm has been established. The speed of the particle was 12 m s⁻¹, which was determined with a digital anemometer. To determine the mass loss, the
weight of the sample is obtained using an analytical balance (accuracy of ±0.0001 g) before the test and the sample is reweighed after having performed the test that had a total period of duration of 6 min, interrupting the test every 2 min. The erosion chamber has a system for varying the angle of impact; for this study the angles of 75°, 85° and 90° were considered. The temperature of the chamber was adjusted to 50 °C for the tests, in order to simulate the extreme temperature in the coast of Oaxaca, Mexico, where some wind turbines were installed using fiberglass coated with gelcoat for blades.

### 2.3. Characterization

The average roughness (Ra) of the composites materials samples was determined with a 3D optical profilometer Alicona Infinite Focus SL, 10 different zones were evaluated. The hardness of the samples was evaluated...
according to ASTM D2583-95 [23], 5 different areas were measured on the surface with a Barcol GYZJ 934-1 durometer. The samples were coated with gold to observe the morphology of the erosion wear surface by an Electron Scanning Microscope Hitachi TM3030 plus. To observe the morphology of the erosive particles, SEM observation was used. The determination of the particle size distribution was carried out in a Ro-Tap Testing Sieve Shaker, 16 sieves were used from a particle size of 1000 $\mu$m to 62 $\mu$m.

3. Results and discussion

3.1. Characterization of the erosive particle

Figure 4 shows the morphology of the sea sand to be applied as erosive particle, it can be seen that most of the particles have an angular shape with different peaks. This morphology strongly influences the dry erosion resistance, because it tends to cause greater wear than the particles that have a round morphology [24].

Figure 5 shows the chemical composition obtained by EDS of the sea sand used in the experimentation. The strong presence of silicon and oxygen can be observed, there is also a smaller proportion of sodium, phosphorus, titanium, potassium, aluminum, calcium, iron, manganese and magnesium. All these elements are characteristic of the sea sand of the beaches of Mexico [25].

The particle size distribution of sea sand is shown in figure 6, which was obtained by means of the sieving method. From the observed distribution it was determined that the average particle size was 300 $\mu$m.

3.2. Roughness and hardness of samples

The roughness and hardness of the glass and carbon fiber samples, with and without gelcoat, are shown in figures 7(a) and (b). Table 1 shows the average values of the roughness and hardness of each sample. Dispersion can be observed between the roughness measurements in the samples containing gelcoat. On the other hand, the samples that do not have gelcoat on their surface show a lower dispersion in the roughness data; this indicates the
presence of a homogeneous surface. It is observed that samples of glass and carbon fiber without gelcoat have a higher hardness than with gelcoat, this is due to the brittleness of the gelcoat, which is a polyester resin [26].

3.3. Optical microscopy and SEM of scars
Figure 8 shows the damage generated by the dry erosion tests at a temperature of 50 °C and the three impact angles used (75°, 85° and 90°). It can be observed that the surfaces of the glass fiber samples show severe
scratches and a very defined circular wear pattern, due to their relatively low hardness and in spite of their good thermal properties [27, 28]. On the other hand, the hardness and thermal properties of carbon fiber samples avoid major damage at the end of the test [29], based on this, it is observed that the wear pattern was not formed in its entirety.

For these temperature erosion tests, samples coated with gelcoat have a very noticeable circular wear pattern, due to their thermal characteristics and their mechanical properties [29, 30]. In these samples an accumulation of material detached during the test on its surface was also observed. The erosion wear resistance of gelcoat was very poor.

Figure 9 shows the micrographs on the wear area of the specimens. In glass fiber some cracks can be observed due to the impact of the sand particles [30], in addition, plastic deformation and cutting action were observed. Carbon fiber presented shear action and some small cracks. The fissures are subsequently transformed into cracks that cause the separation of the fibers from the matrix. In the case of the gelcoat coating, small cracks, formation of craters and pitting action were observed as well as material removed that adhered to the surface of the coating (debris).
3.4. Wear mass loss and profilometry

Figure 10(a) shows in 3D the wear zone of the glass fiber surface, in which the damage can be observed in the form of irregularities and scratches that cause the erosion of solid particles of sand at an impact angle of 75°. Figure 10(b) shows the wear zone of the carbon fiber, in this case the solid particles impacted at an angle of 90°, which caused pitting action and formation of craters.

Figure 11 shows the mass loss due to temperature erosion tests of composite materials coated and uncoated with gelcoat. In the case of tests at impact angle of 75° (figure 11(a)), it was observed that carbon fiber had the lowest mass loss and glass fiber with gelcoat showed the greatest amount of mass loss. In the tests carried out at impact angle of 85° (figure 11(b)) there was greater wear in samples with gelcoat, this is because the gelcoat has a lower hardness and the angular sand particles remove the material quickly [31]. Erosion damage at 90° is regularly maximum [32–34], because the erosive particles impact perpendicularly to surface of the material. In figure 11(c) it was observed that the mass loss from erosion wear at 90° is greater in all materials, this confirms the brittle erosion behaviour and results in a rougher surface after the tests [35].

Table 2 shows the average wear mass loss of the samples subjected to dry erosion test at temperature of 50°C. It is observed that the sample with the lowest mass loss is in carbon fiber samples at impact angle of 85° and the sample with the highest mass loss was glass fiber composite with gelcoat at impact angle of 90°. In the tests carried out, the carbon fiber presented the lowest mass loss compared to the other samples evaluated. This confirms what has been reported in other studies, where it was shown that carbon fiber has excellent mechanical properties and wear resistance [36].

Figure 9. Wear mechanisms identified by SEM.

Figure 10. 3D profilometry of wear region formed on the sample of (a) fiberglass and (b) carbon fiber.
Figure 12 shows the wear profilometry of the samples due to dry erosion tests at temperature of 50 °C. It can be seen some similitudes between the geometries of profiles at different impact angle, but also some important differences in the wear depths were found. In the case of impact angle of 75° (figure 12(a)), it was observed that carbon fiber had an average wear depth of 28 μm, showing a saw tooth aspect, due maybe for the bidirectional 0/
90° of the fabric. For this material, the greatest wear depths were found at 90° impact angle (figure 12(c)). In the case of fiber glass, the lowest wear depth was found when 85° impact angle was used (figure 12(b)) and the greatest wear depth was in the tests at an impact angle of 75°.

### 3.5. Proposal

As is shown in table 2, under the particular conditions carried out in this work, carbon fiber had better erosion resistance than fiber glass, however, it is not recommended, in terms of costs, to manufacture the blade of carbon fiber, so the proposal, that derives from this experimental work, is to apply, on the leading edge, a carbon fiber coating in the form of thin tape. An schematic representation of this proposal is shown in figure 13. Finally, no experimental research works have been found that report similar results, particularly, in wind turbines applications and using sea sand as erodent.

**Table 2.** Average values of wear mass loss of the evaluated samples.

| Sample                  | Impact angle 75° | Impact angle 85° | Impact angle 90° |
|-------------------------|------------------|------------------|------------------|
| Glass fiber             | 1.27             | 0.9              | 0.93             |
| Glass fiber with gelcoat| 2.57             | 2.07             | 4.13             |
| Carbon fiber            | 0.87             | 0.30             | 0.47             |
| Carbon fiber with gelcoat| 3.50             | 2.93             | 3.70             |

**Figure 12.** Profilometry of the samples evaluated by temperature erosion at impact angles of (a) 75°, (b) 85° and (c) 90°.
4. Conclusions

- Carbon fiber composite material had, approximately, 3 times more resistance to erosive wear than fiberglass.
- The materials coated with gel coat erode quickly and exhibit a semi-fragile erosion behavior.
- The most significant mechanisms found in the carbon and glass fiber composite materials were: pitting action, formation of cracks, cutting action on fibers, plastic deformation mainly on matrix, formation of craters on gelcoat and accumulation of debris.
- It was found that surface roughness had a significant impact in wear erosion of the composites materials tested. An increase in roughness can accelerate the damage by the erosive particle, mainly at low impact angles (75°).
- The average wear depth in carbon fiber were between 30 and 70 μm, while in fiberglass were greater than 100 μm.
- The use of a thin laminate of carbon fiber to protect the leading edge of wind turbine blades of fiberglass can help to reduce considerably the erosive phenomenon, increasing the life of blades.
- According to experimental tests made in this work, a temperature of 50 °C did not show to be a determining factor in erosion resistance by sea sand particles on carbon and glass fiber, confirming the thermal stability of these composite materials.

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