Solid particle erosion resistance and electromagnetic shielding performance of carbon fiber reinforced polycarbonate composites

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Abstract
Thermoplastic polycarbonate (PC) has attracted tremendous attention due to its superior recyclability and environmental friendliness compared with thermosetting resins. In this work, thermoplastic polycarbonate was used as the matrix material and the solid particle erosion resistance of carbon fiber reinforced polycarbonate (CF/PC) composites, as well as the influence of solid particle erosion on the mechanical properties of composites were studied systematically. The results indicated that the maximum erosion angle for CF/PC is 30°, and samples are easier to be eroded when impacted in parallel direction to CF than the vertical. In addition, after 2 min solid particle erosion, the tensile strength and the maximum load decreased by 11.9% and 11.8% respectively, and flexural properties of all samples declined (flexural modulus by 49%, flexural strength and maximum load by 14.6%, flexural strain by 11.9%). Finally, an excellent EMI shielding effectiveness (SE) of around 40 dB over 12 GHz to 18 GHz was achieved for composites. Due to the destruction of CF/PC composite structure and the reduction of its thickness, its EMI shielding effectiveness was greatly decreased to 28 dB after sand erosion.

1. Introduction

In recent years, these composites with high strength-to-weight ratio, erosion resistance and high modulus have exhibited a rapid growth trend [1–4]. Thermoplastic materials like polyamides (PA) and polypropylene (PP) have been vastly investigated due to the advantages of recyclability and environmental protection [5–17]. Different from thermosetting plastics, thermoplastics are easier to solidify and faster to produce. But the low solid erosion resistance of typical thermoplastics material limits its application. Continuous fibers such as glass fiber and carbon fiber were often added into the matrix to improve the solid erosion resistance and mechanical property of thermoplastics materials [18–22].

Carbon fiber (CF) has attracted tremendous interest due to its excellent properties involving the high tensile property, erosion resistance and excellent electromagnetic (EMI) shielding performance [23–27]. Zhao et al [28] found that mechanical properties of CF reinforced polymer (CFRP) composites are better along fiber direction than that in vertical direction. Pool et al [29] compared four composites: CF reinforced polyimide (CF/PI), CF reinforced polyphenylene sulfide (CF/PPS), aramid fiber reinforced epoxy (AF/EP) and CF reinforced EP (CF/EP), it was demonstrated that CF/PPS composite had the best property for sand erosion resistance. Mathias et al [30] found that composite material was eroded easily than matrix polymer. Miyazaki [31] reviewed the papers of solid particle erosion and mentioned that the maximum erosion angle of composite material was larger than that of corresponding matrix. Ameli et al [32] reported that the addition of CF could improve the EMI shielding property of composites. A plenty of studies regarding the solid particle erosion behavior of CF reinforced...
thermoplastics were also conducted, but the researches on the solid particle erosion of CF reinforced thermoplastic polycarbonate (CF/PC) has rarely been reported.

In this work, CF/PC composites were studied. Solid particle erosion test was conducted to explore the solid particle erosion resistance of CF/PC composites. Meanwhile, mechanical properties before and after erosion were also compared. Scanning electron microscope (SEM) and ultra-depth of field tester were employed to observe the surface of composites. Furthermore, we also measured the electromagnetic shielding performance of CF/PC composites before and after solid particle erosion.

2. Experimental section

2.1. Sample preparation
PC used in this study was Makrolon 2407 model of Covestro company in Germany. CF with density of 1.5 g cm$^{-3}$ was T700 series, it was bought from Covestro company. Firstly, CF was made into single layer belt under the function of infiltration by liquid PC. Then the unidirectional tapes were laid as laminate through thermo-compression formation. The Marshalling sequence of unidirectional tapes were $(0^\circ/90^\circ/+45^\circ/-45^\circ)$, its sketch is shown in figure 1. CF/PC plates consisted of 8 layers unidirectional tapes with a thickness of 2 mm. The fraction of CF in laminate was 60 wt%.

2.2. Sand erosion testing
Sand-blasting equipment (model STR-9060) was used to investigate the erosion resistance of CF/PC composites. Figure 2 is a schematic diagram of erosion test sketch map. Samples were tested at room temperature ($25^\circ$ C). The angular solid particles were SiC with the average diameter ranging from 300 to 800 $\mu$m. The SiC particles were accelerated by compressed air of 0.34 MPa and erupted through air jet nozzle. The nozzle made of boron carbide (B$_4$C) has a diameter of 6 mm. The distance between nozzle and fixture was 30 mm. Samples were impinged for 2 min at different angles ($30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$ and $90^\circ$) to explore the maximum erosion angle. Furthermore, under the maximum erosion angle, specimens were impacted for two different directions (parallel and vertical to CF) with duration from 0 to 300 s.

2.3. Tensile property measurement
The universal testing machine (model INSTRON 5585) was adopted to test the mechanical performance of CF/PC composites. Specimens before and after erosion were conducted and contrasted at least seven times. The tensile rate was 1 mm min$^{-1}$ and the gauge length was 50 mm according to GB-T 1040 standard. The specimen size was 170 mm $\times$ 12 mm $\times$ 2 mm.

2.4. Flexural property test
The influence of sand erosion on the flexural properties was studied according to GB-T 9341-2000 standard by the universal testing machine (model INSTRON 5585). Samples were measured at a speed of 1 mm min$^{-1}$ and with a span of 24 mm. The specimen size was 80 mm $\times$ 10 mm $\times$ 2 mm. The flexural properties were determined at least seven specimens.
2.5. Observation of surface morphology
In order to verify the influence of sand erosion on surface morphology of CF/PC composites, topography of specimens before and after erosion were analyzed via scanning election microscope (SEM). Samples were sprayed with thin layer gold for 60 s at 10 mA to make them more conductive.

Furthermore, the three-dimensional topography of samples after sand erosion was observed. Specimens were characterized by super depth microscope (model Leica DVM6).

2.6. EMI shielding performance test
The EMI shielding performance of CF/PC composites was characterized according to ASTM standard D4935 by electromagnetic shielding meter (model E5071C). Specimens were chopped into disks with diameter of 15 mm. The frequency area was from 1 GHz to 20 GHz. During the EMI testing, specimens dimension was bigger than the chamber a bit to insure the accuracy of the results.

3. Results and discussion
3.1. Solid particle erosion on CF/PC composites
Figure 3 exhibits the results for CF/PC composites eroded at different angles. It’s clearly that the weight loss of samples decreased with the increase of erosion angle, which is dependent on the nature of material itself. Researches about the brittleness and ductility of materials can be distinguished through erosion angle. For ductile material, whose erosion resistance was worst under 30°, while the maximum erosion angle of brittle material was 90° under the same test condition [33].
Furthermore, solid particle erosion tests were conducted on samples in two different impingement directions: parallel and vertical to figure 4(a) shows the results for CF/PC composites eroded with different time. Weight loss of specimens increased linearly with erosion time. With a duration of 120 s, the erosive behavior in two impinge directions were similar. While the weight loss of CF/PC composite impinged in parallel direction was 23.4% more than that in vertical direction after 120 s. The reason is that only the PC matrix is eroded in the first 120 s. When most of the fibers are exposed, solid particles impinged in the parallel direction are easier to be embedded into the fibers, aggravating the expanding of crack and the stripping of matrix. The photographs of real samples are reflected in figure 4(b).

3.2. Tensile property
The influence of solid particle erosion on the tensile property of CF/PC composites were determined by tensile testing. Figure 5 presents the change of tensile strength and maximum load before and after impinging. The tensile property of CF/PC composite decreased obviously after 2 min erosion, where the tensile strength and the maximum load decreased by 11.9% and 11.8% respectively. Continuous erosion of solid particles will results in fiber fracture, this lead to the decline of fiber tensile properties. In a word, 2 min of solid particle erosion has little effect on the tensile properties of materials.

3.3. Flexural property
The flexural property of CF/PC composites before and after erosion is shown in figure 6. The modulus of specimen decreased 49% after erosion. The eroded CF/PC composites’ maximum load and flexural strength decreased by 14.6% and the flexural strain declined by 11.9%. Conclusion can be drawn that the continuous
impinge of solid particles causes a decrease in the bending properties of CF/PC composite. The modulus of CF/PC composite was affected greatly by sand erosion, and the break of CF led to a serious deterioration of bending resistance.

Figure 6. Flexural property of CF/PC composites before and after erosion.

Figure 7. Surface morphologies of CF/PC composites (a): uneroded, (b): sand erosion for 2 min, (c): partial enlargement of (b) and (d): partial enlargement of (c).
3.4. Surface topography
The surface morphologies of CF/PC composites before and after erosion is demonstrated in figure 7. Surface of specimens were smooth without erosion (from figure 7(a)), but they were worn severely after eroded 2 min at 30° (from figures 7(b)–(d)). The matrix on the surface of composite material falls off, lots of fragments and pits were observed from figure 7(b). As seen in figure 7(c), the resin matrix was eroded by solid particles and some fibers were exposed. Under the continuous impact of solid particles, parts of CF fractured and separated from the matrix (figure 7(d)).

Figure 8 exhibits the three-dimensional morphologies on sample surface before and after sand erosion. In figure 8(a), no evident ups and downs (bump sand hollows) were observed on the surface of un-eroded sample. However, a lot of scratch and abrasion are noticeable on the surface of CF/PC composite (see figure 8(b)). Deep chisel pit was generated on specimen by sand blasting, indicating the severe erosion of specimens.

3.5. Electromagnetic shielding effectiveness
The EMI SE curve is exhibited in figure 9. The total value of electromagnetic shielding is indicated as SET. The value of absorbing electromagnetic wave and reflecting electromagnetic wave are respectively marked as SEA and SER. From figure 9(a) we found that CF/PC composites have shielding effect in Ku band from 12 GHz to 18 GHz. The average value is 40 dB, indicating an excellent shielding property of specimens. It can be seen from the picture that the reflection of electromagnetic waves is the mainly approach of CF/PC composites to reach shielding effect. The electromagnetic shielding effectiveness of material decreased obviously from 40 dB to 28 dB after erosion (see figure 9(b)). The CF/PC composites had a decrease of thickness after sand erosion, resulting in the poor shielding performance. This statement can be confirmed by the experimental results in figure 8. In addition, the CF exposed after erosion contributes to the absorption of electromagnetic waves.
4. Conclusion

This work suggests that CF/PC composites have tensile and flexural properties, erosion resistance and EMI shielding performance. Specific conclusions are as follows:

1. By solid particle erosion, we demonstrated that CF/PC composites are most eroded at 30°, presenting a ductile erosion behavior. Furthermore, the erosion resistance of CF/PC in parallel direction is worse than that in vertical direction.

2. Compared to un-eroded samples, the flexural modulus and flexural strain reduced 49% and 11.9% respectively after erosion. The flexural strength and maximum load of CF/PC composites all decreased by 14.6%. The tensile strength and maximum load severely had a decline of 11.9% and 11.8%.

3. The morphology confirms that solid particle erosion on specimens will take away matrix and CF, causing deep chisel pit on the surface of sample.

4. The shielding value was 40 dB of CF/PC from 12 GHz to 18 GHz. After sand erosion, the EMI performance of the material decreased to 28 dB owing to the decrease in material thickness.

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