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Study on Erosion of Carbon Fiber Reinforced Plastic Composite

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탄소섬유강화복합재료의 마식에 관한 연구

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Abstract The solid particle erosion behaviour of unidirectional carbon fiber reinforced plastic (CFRP) composites was investigated. The erosive wear of these composites was evaluated at different impingement angles (30°, 45°, 60°, 90°), different impact velocities (40, 55, 60, 70m/s) and at three different fiber orientations (0°, 45°, 90°). The erodent was SiC sand with the size 50-100㎛ of irregular shapes. The result showed ductile erosion behaviour with maximum erosion rate at 30° impingement angle. The fiber orientations had a significant influence on erosion. The erosion rate was strongly dependent on impact velocity which followed power law $E \propto V^n$. Based on impact velocity (V), impact angle (α) and fiber orientation angle (β), a method was proposed to predict the erosion rate of unidirectional fiber reinforced composites.

Ky Wrds : Erosion Rate, CFRP, Particle Velocity, Impingement Angle

요 약 일방향 탄소섬유 강화 복합재료(CFRP)의 고체입자 마식 거동을 다양한 충돌각도 (α), 속도 (V) 및 섬유 방향 (β)에 대하여 연구하였다. 실험결과 30o 충돌각도에서 최대 마식률을 나타내었고, 마식률은 멱함수 법칙 $E \propto V^n$ 에 따라 충돌속도에 크게 의존하였다. 본 연구에서는 이상의 결과로부터 일방향 탄소섬유 강화 복합재료의 마식률을 충돌속도, 충돌각도 및 섬유방향 각도로부터 예측하는 방법을 제안하였다.

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. Due to the operational requirements in dusty environments, the erosion characteristics of the polymeric composites may be of high relevance. It is widely recognized that polymers and their composites have a poor erosion resistance and erosion rate of polymer composites is usually higher than that of neat polymers [1].

Many researchers [1-8] have investigated the solid particle erosion behaviour of polymers and the composites. The erosion behaviour of materials can be broadly classified as ductile and brittle depending on the variation of the erosion rate with impingement angle [1,2,7,9]. However, this classification is not absolute as the erosion behaviour of a material has a strong dependence on erosion conditions such as impingement angle, impact velocity and erodent properties. In the literature, it was found that the erosion rate follows power law behaviour with particle velocity, $E \propto V^n$ and the erosion behaviour of polymers and the composites has been characterized by the value of the velocity exponent, n [8].

The objective of the present paper is to study the solid particle erosion characteristics of unidirectional carbon fiber reinforced plastic composites (CFRP) under various experimental conditions and propose a general method to predict the erosion rate.

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2. Experimental

2.1 Material

In this study, unidirectional continuous carbon fiber reinforced plastic composite (CFRP) was tested. Dimension of the specimens was 30 ㎜ × 20 ㎜ × 4.50 ㎜. Properties of the specimen are given in Table 1. Specimens with three different types of fiber orientation (0°,45°,90°) were investigated. Erosive wear tests were carried out at four different impingement angles (30°, 45°, 60° and 90°) with different fiber orientation angles.

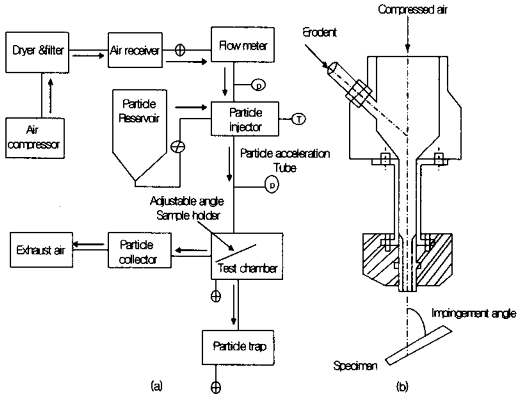
2.2 Experimental setup and procedure

A schematic diagram for the solid particle erosion test used in the present study is shown in the Fig.1. SiC particles with the size 50-100 ㎛ of irregular shape were selected as erodent as shown in Fig. 2. The distance between the sample holder and the nozzle was 10 ㎜. The impingement angles were adjusted by turning the sample holder. The impact velocities of particles was controlled by varying the flow rate of compressed air, and was set to be 70, 60, 55, and 40 m/s.

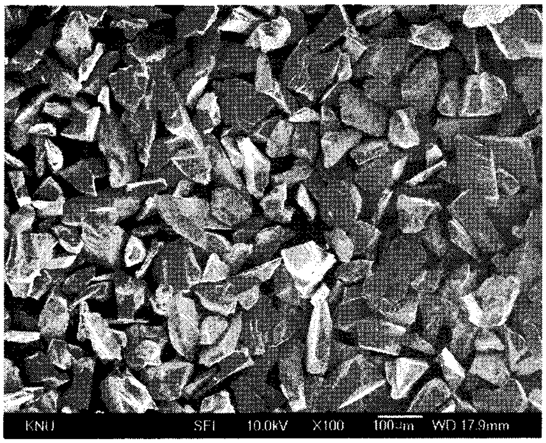
The velocity of the eroding particles was measured using the double disk method proposed by Ruff and Ives [5]. The erosion rate was defined as the weight loss from specimen surface per unit weight of impinged particles after 600g of particles was impinged. The weight loss after impingement was measured by an electronic balance with an accuracy of 0.01㎎.

[Table 1] Properties of unidirectional continuous carbon fiber reinforced plastic composite (CFRP)

Material	Density (g/cm^3)	Elastic modulus (GPa)	Tensile strength (MPa)	Fiber content (vol.%)
Composite	1.70	195	3.525	60



[Fig. 1] Experimental setup: (a) Schematic diagram of erosion tester; (b) Details of nozzle

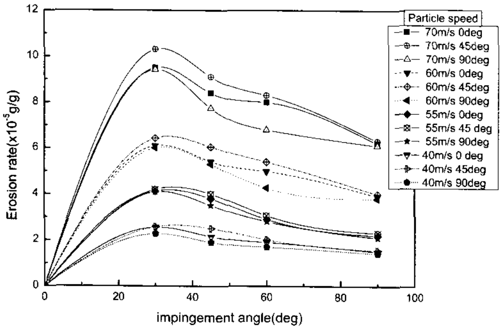


[Fig. 2] Impingement SiC particles

3. Results and Discussion

3.1 Effect of impingement angle

Fig. 3 represents the typical relationship between erosion rate and impingement angle. It can be seen that the erosion rate was maximum at 30° impingement angle for all fiber orientations and impact velocity. When erosion rate is measured as a function of impingement angle, ductile and brittle materials have shown a marked difference in their response [9]. 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 above two categories, have shown a semi-ductile behaviour with maximum erosion occurring in the range of 45°-60° [2]. However, according to Hutchings [3] materials can be either ductile or brittle as the erosion conditions such a impingement angle, impact velocity and erodent properties such as shape, hardness, size, particle flux etc. are changed. Manish Roy et al.[4] reported that composites having a thermo-set matrix(epoxy and phenolic) behaved in a brittle way while the composites with thermoplastic matrix(polyester) responded in ductile manner. Tewari et al. [1] investigated the solid particle erosion behaviour of unidirectional carbon and glass fiber-epoxy composites using steel balls and found that both carbon and glass fiber-epoxy plastic showed semi-ductile behaviour with maximum erosion rate at 60° impingement angle. N.M. Barkoula et al. [2] investigated the erosive wear behaviour of glass fibre reinforced thermoplastic polypropylene composites and maximum erosion rate was found at 30° impingement angle. In the present study, the carbon fiber reinforced plastic composites showed ductile behaviour as maximum erosion rate was dominated at 30° impingement angle for all particle velocity. Moreover, the erosion rate decreases with increase of impingement angle.



[Fig. 3] Erosion rate vs. impingement angle

3.2 Effect of fiber orientation

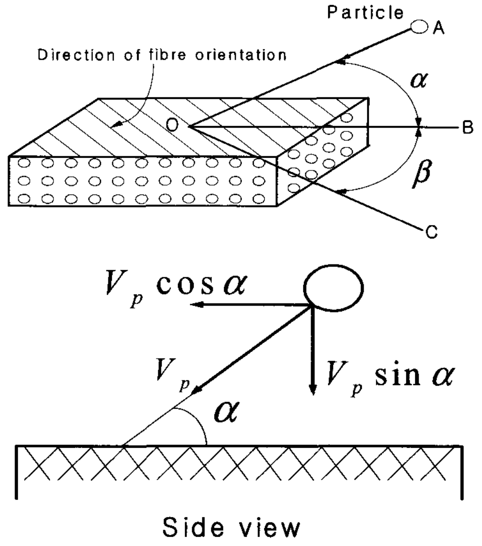
The fiber orientation angle plays a important role in erosive wear. Earlier, researchers [1,2,6] investigated the influence of fiber orientation on erosive wear, and pointed out the clear dependence of erosive rate on fiber orientation. According to Tewari et al. [6], erosion rates decrease with increase of fiber orientation angle. The order of erosion rate at 0° fiber orientation > at 45° fiber orientation > at 90° fiber orientation. The effect of fiber orientation angle is more significant at higher impingement angle. According to K. Tsuda et al. [6], erosion rate increase with increases of fiber orientation angle at all impingement angles and magnitude of effect of the fiber orientation angle is larger at lower impingement angle. According to N.M. Barkoula et al. [2], erosion rate for 0° fiber orientation is higher than that of for 90° fiber orientation at low impingement angle(30°). In the present study, it is observed that erosion rate for 45° fiber orientation is higher than that of for 0° and 90° fiber orientation at all impingement angles except 90°. At 90° impingement angle, the fiber orientation showed hardly any influence on erosive wear. For other impingement angles, the order of erosion rate at 45° fiber orientation > at 0° fiber orientation > at 90° fiber orientation. These results are in disagreement with some previous observations [1,2,6].

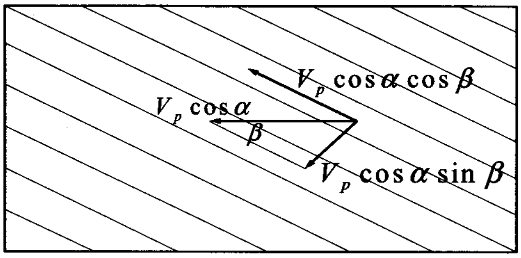
3.3 Effect of particle Velocity

Erosion rate is strongly dependent on impact velocity of erodent particles. From Fig. 3 it is evident that erosion rate is remarkably higher at higher impact velocity. If solid particle impacts on a composite material, the velocity is decomposed to two components, vertical component $V_p sin\alpha$ and horizontal component $V_p cos\alpha$. The latter one is divided into two components against the fiber axis, perpendicular $V_p cos\alpha sin\beta$ and parallel $V_p cos\alpha cos\beta$ as shown in Fig. 4. Thus erosion rate is assumed to be expressed with three velocity components of $V_p sin\alpha$, $V_p cos\alpha sin\beta$ and $V_p cos\alpha cos\beta$ as follows

$$E_r = A(V_p \sin\alpha)^n + B(V_p \cos\alpha \sin\beta)^n + C(V_p \cos\alpha \cos\beta)^n \tag{1}$$

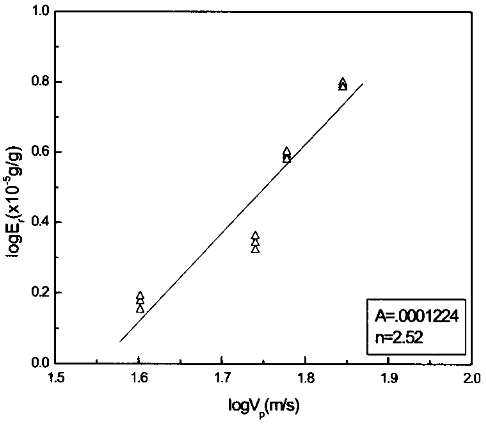
$V_p cos\alpha cos\beta$ has very low impact on fiber and it plays a role only in case of abrasive erosion of matrix. Here A, B and C are velocity coefficients and n is velocity exponent for given impact velocity(V), impingement



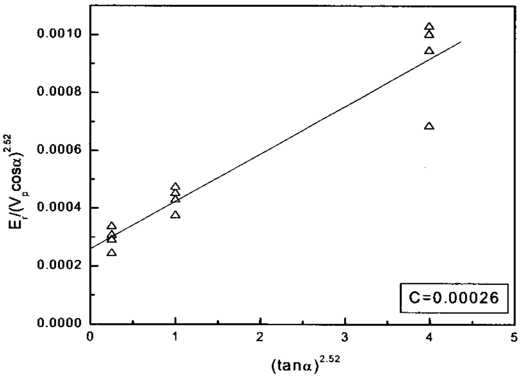


Top view

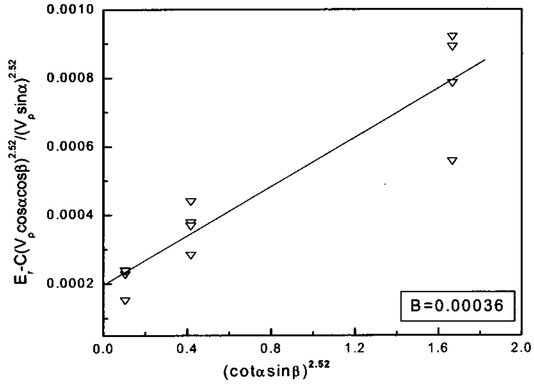
[Fig. 4] Explanation of velocity components



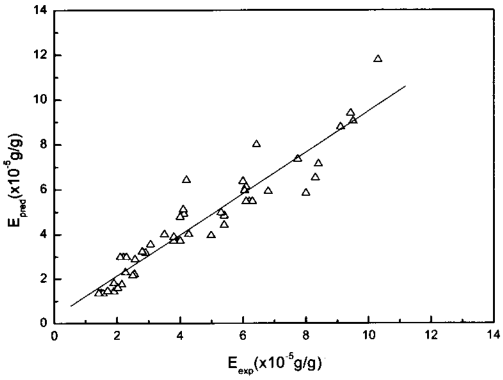
[Fig. 5] Relationship between erosion rate and impact velocity for α=90°, β=0°, 45°, 90°, V_p=40, 55, 60, 70 m/s



[Fig. 6] Relationship between erosion rate and various factors for β=0°; α=30°, 45°, 60° and V_p=40, 55, 60, 70 m/s



[Fig. 7] Relationship between erosion rate and various factors for β=45°, α=30°, 45°, 60° and V_p=40, 55, 60, 70 m/s.



[Fig. 8] Comparison of experimental and predicted values of erosion rate

angle (α), fiber orientation angle(β) and dependon the properties of the target and particle materials. The values of n and A are obtained from Fig. 5. Considering α=90° in Eq.(1), they were 2.52 and 0.0001224 respectively. When fiber orientation is 0° and impingement angle is less than 90°, $V_p cos\alpha sin\beta$ has no effect on erosion by Eq.(1). Substituting the obtained value of n and β=0° into Eq.(1), Eq.(2) is acquired as follows

$$E_r = A\,(V_p\sin\alpha)^{2.52} + C(V_p\cos\alpha)^{2.52}$$

$$E_r/(V_p\cos\alpha)^2 = C + A\,(\tan\alpha)^{2.52} \qquad (2)$$

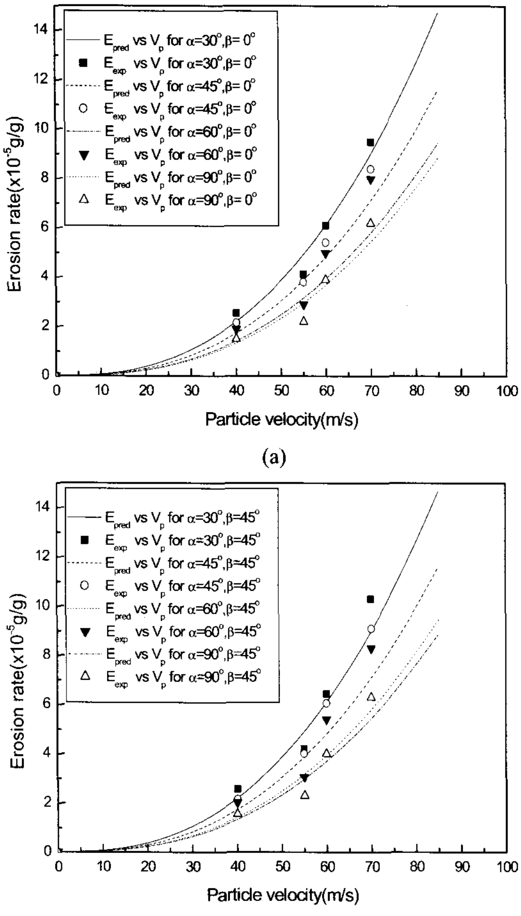
Value of C can be obtained as 0.00026 from Fig. 6. When fiber orientation is 0°<β<90° and impingement angle(α) less than 90°, all three velocity components have effect on erosion rate. Using all above obtained values, Eq.(1) is rearranged as follows

$$
\begin{aligned}
&E_r - C(V_p cos\alpha cos\beta)^{2.52} \\
&\quad = A(V_p sin\alpha)^{2.52} + B(V_p cos\alpha sin\beta)^{2.52} \\
&(E_r - C(V_p cos\alpha cos\beta)^{2.52})/(V_p sin\alpha)^{2.52} \\
&\quad = A + B(cot\alpha sin\beta)^{2.52}
\end{aligned} \tag{3}
$$

Here, value of B can be determined as 0.00036 from Fig. 7. Thus the form of Eq.(1) is finalized as following

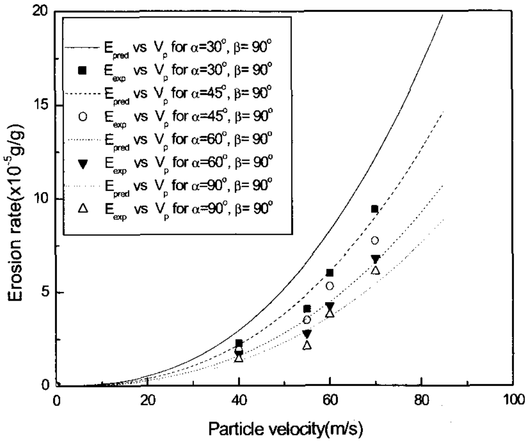
$$
\begin{aligned}
E_r = &\,0.0001224(V_p sin\alpha)^{2.52} \\
&+ 0.00036(V_p cos\alpha sin\beta)^{2.52} \\
&+ 0.00026(V_p cos\alpha cos\beta)^{2.52}
\end{aligned} \tag{4}
$$

Implementing the experimental conditions(V_p, α, β) into Eq.(4), the erosion rates were calculated and compared with experimental results in Fig. 8.



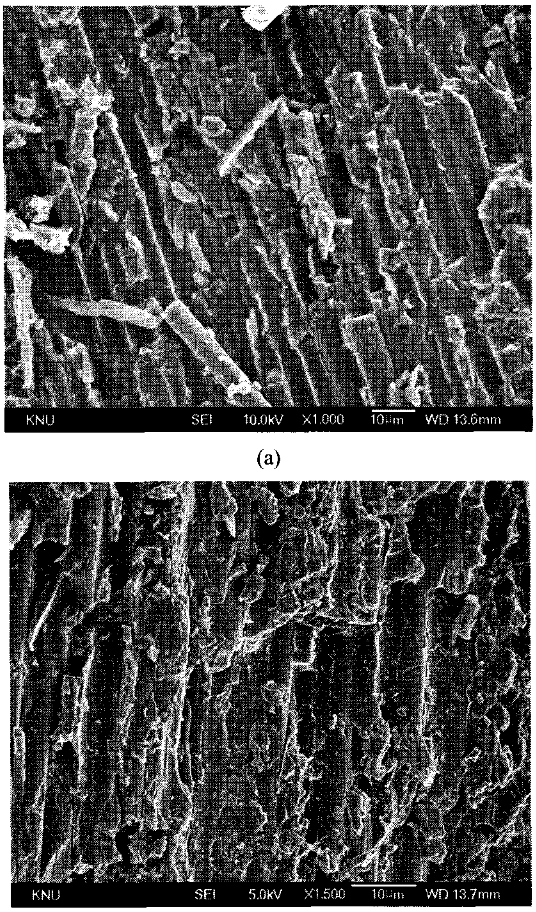
(a)

(b)



(c)

[Fig. 9] Comparison of predicted and experimental value of erosion rate with impingement angle



(a)

(b)

(c)

[Fig. 10] Impact velocity 70m/s, impingement angle 30°; (a) fiber-direction 0°, (b) fiber-direction 45°, (c) fiber-direction 90°

As both results agree well, it is concluded that this procedure is applicable as a general way to estimate the erosion rate of unidirectional fiber reinforced composite. To confirm the erosion rate for various particle velocities under various experimental conditions (α, β), the relationships between erosion rate and particle velocity were plotted as shown in Fig. 9. As experimental results holds well with the plotted curve, it can be concluded that this procedure can be used as a general way to estimate the erosion rate of unidirectional fiber reinforced composite.

3.4 Surface morphology of eroded surface

Fig. 10 shows a SEM of surfaces eroded at an impingement angle of 30° at impact velocity 70 m/s and three fiber orientations(0°, 45°, 90°). Fig. 10(a) shows the surface with 0° fiber orientation. It is seen that particle flow creates fiber cracking and subsequent fiber removal. Some of the bent fibers were broken but remained due to their good adhesion. Fig. 10(b) shows the surface with 45° fiber orientation. It is seen that there is a local removal of matrix material from the surfaces resulting in exposure of fibers to the erosive environment. The fibers are still held firmly in place by the undamaged matrix material surrounding them. Fig. 10(c) shows the surface with 90° fiber orientation. The matrix covering the fiber seems to be chipped off showing the craters with an array of almost intact fibers.

4. Conclusion

(1) The influence of impingement angle on erosive wear of composites exhibited ductile erosive wear behaviour with maximum erosion at 30° impingement angle.

(2) The fiber orientation had a significant influence on erosion. Erosion rate was higher for 45° fiber orientation than 0° and 90° fiber orientations for all impingement angles except 90°. At 90° impingement angle, fiber orientation had hardly any influence on erosion.

(3) The morphologies of eroded surfaces observed by SEM suggest that the overall erosion damage of composites consists of matrix removal and exposure of fibers, fiber cracking and removal of broken fibers.

(4) Considering impact velocity, impingement angle and fiber orientation, a general method was proposed for predicting the erosion rate of unidirectional fiber reinforced composites.

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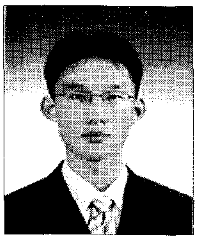

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