Prediction of the Residual Tensile Strength after Solid Particle Erosion of UD-GF/PP Composites

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ABSTRACT: In the present work the residual tensile strength of unidirectional (UD) glass fibre (GF) reinforced thermoplastic polypropylene (PP) composites after oblique (30°) solid particle erosion was investigated as a function of the impact time and relative fibre orientation (parallel, Pa and perpendicular, Pe).

A semi-empirical approach initially developed to predict the residual tensile strength after single normal impact [1] and latest successfully adopted for thermosetting carbon fibre/epoxy (CF/EP) composites [2] worked well for the thermoplastic UD-GF/PP composites studied. A very good agreement was found between the experimental results at 30° erosion angle and the theoretical prediction in both Pa and Pe erosion directions. A comparison of the strength degradation behaviour of UD-GF/PP and CF/EP composites showed that UD-GF/PP presented the onset of its strength degradation considerably earlier but it preserved a higher relative residual tensile strength than CF/EP. The erosion direction in UD-GF/PP had marginal effect on the energy threshold resulting in severe strength degradation, whereas it showed a pronounced effect on the residual tensile strength.

KEY WORDS: solid particle erosion, GF/PP composites, erosion direction, residual properties, modelling.

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INTRODUCTION

IT IS GENERALLY recognised that polymer composites with both discontinuous and continuous fibre reinforcement possess high specific (i.e. density related) stiffness and strength when measured in plane, therefore, such composites are frequently used in various engineering parts in automobile, aerospace, marine, and energetic applications [3–5]. Due to the operational requirements in dusty environments, the erosion characteristics of the polymeric composites may be of high relevance. Key aspects when selecting a material system is to know how its properties are changing as a function of externals ("service") conditions and in what extent the residual values can be predicted.

Solid particle erosion is regarded as a repeated impact procedure which results to both material removal and strength/stiffness reduction. It has been reported that composite materials present a rather poor erosion resistance [3–12]. As a consequence, a significant degradation in tensile strength mainly due to matrix cracking, delaminations and fibre breakage is observed. An increase in strain to failure of the matrix generally results in improved residual strength of the composite after impact, but this improvement is limited because of the need to maintain satisfactory performance at high temperatures and under severe environmental conditions [13]. Although thermoplastics appear to meet the above requirements, they have received little attention comparatively to thermosetting composites [13]. Majority of the studies concentrated on the normal impact of carbon fibre/epoxy (CF/EP) laminates, and there are many reports on the residual behaviour of this system after impact, as well. The failure mode in thermoset matrix composites is a complex process involving matrix micro-cracking, fibre–matrix debonding, fibre breakage and material removal [3,7–8]. Thermoplastic matrix composites behave differently. The higher matrix toughness allows substantial plastic deformation which absorbs a great extent of the impact energy [3]. The matrix is uniformly grooved due to microcutting and microploughing which results in maximum material removal at oblique impact, viz. 30°.

As different mechanisms of material removal govern the erosion of thermoplastic matrix composites, the main aim of this study was to evaluate whether the model recently proposed for the prediction of the residual characteristics of a typical thermosetting composite viz. CF/EP [2] holds also for the case of unidirectional glass fibre reinforced polypropylene (UD-GF/PP) composites. This model takes under consideration the visco-elastic behaviour of the material and its energy absorption capacity expressed through $\tan\delta$ [1].

Different trends have been reported in literature about the role of the relative fibre orientation on the erosive wear especially for thermosetting composites [3,7,10,11, 14,15]. The effect of relative fibre orientation was proved recently in a GF/PP composite with interface modifier [16]. It was concluded that the relative fibre orientation affects strongly the erosive wear at oblique impact (30°). For the UD specimens with fibres aligned parallel (Pa) to the impinging direction, the erosive wear was considerably higher than at perpendicular (Pe) alignment to the jet. No influence was observed at 60 and 90° impact angles. Therefore, a comparison of the residual tensile strength of Pa and Pe erosion directions after oblique-30°-impact was a further purpose of this study.

Finally, it was interesting to compare the onset of strength degradation and the preserved percentage of the initial tensile strength in composites showing ductile (UD-GF/PP) and brittle (CF/EP [2]) erosion behaviours.

EXPERIMENTAL

Materials

In the present study, the PP matrix was reinforced with continuous UD-GF (ϕ17μm) and processed into parts via hot pressing. The material was provided in the form of tapes by Fact (Future Advanced Composites & Technology Ltd. Kaiserslautern, Germany). The PP matrix was provided without coupling agent. The fibre weight fraction (wt.%) of the composition was 40 wt.% which corresponds to 20 vol.%. Rectangular plates of $120 \times 10 \times 2\,\text{mm}^3$ were cut from the cured laminates by a diamond saw and subjected to erosion tests. These specimens were afterwards subjected to tensile tests.

Testing Methods

EROSION

All the erosion tests were performed in a sandblasting chamber (Figure 1) by sharp, angular corundum with a particle size between 60 and 120 μm at 30°, 60° and 90° impact angle. The distance between the sample holder and the nozzle was constant (160 mm). Though the speed of the erodent particles can be varied by modifying the air pressure in the nozzle, it was kept constant at ca. 70 m/s according to a double slat disk calibration method [17]. This resulted in a 1.02 J/s impact energy rate at 30° impact angle. All erosion tests were performed at room temperature. The eroded area was also constant as a steel cover frame with a circular opening (ϕ10) was placed on the surface of the specimens. The specimens were eroded in Pa and Pe directions (cf. Figure 1).

The composite weight loss was recorded as a function of erosion time by a precision balance (AT261 Mettler Toledo, sensitivity 50 μg). Before weighing, the corundum particles were removed from the specimen surface by air blasting.

DYNAMIC MECHANICAL THERMAL ANALYSIS (DMTA)

The viscoelastic response of the virgin material was studied by DMTA. An Eplexor™ 150 N (Gabo Qualimeter, Ahlden, Germany) DMTA machine has been employed to carry

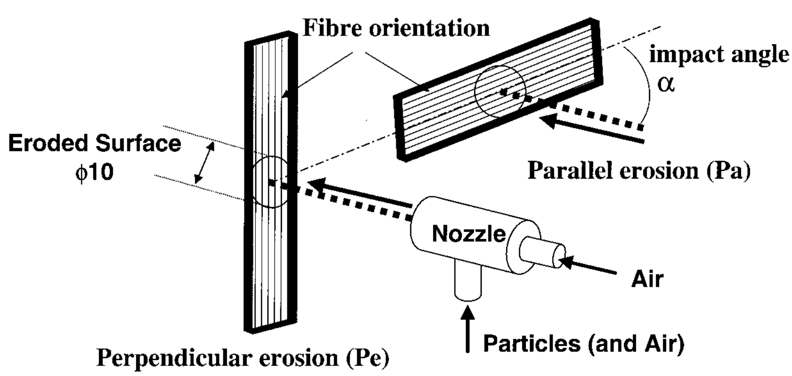

Figure 1. *Schematic representation of the erosion test set-up. Note: this figure indicates the erosion direction and the related designation of the UD composites.*

out the tests. Rectangular specimens $60 \times 10 \times t$ (length $\times$ width $\times$ thickness) were subjected to tensile loading composed of a static preload of 10 ± 1 N on which a sinusoidal wave of 5 ± 0.5 N at 5 Hz frequency was superimposed. Heating occurred at a rate of 1°C/min and a temperature range between -100 and 180°C has been scanned.

TENSILE MECHANICAL CHARACTERISTICS

Tensile properties were measured on a Zwick™ 1485, 250 kN (Ulm, Germany) universal testing machine equipped with an incremental mechanical extensometre at a crosshead speed of 2 mm/min. All tensile tests were performed at a direction parallel to the fibre orientation, at ambient temperature (25 ± 2°C), according to ISO 527-4 [18].

RESULTS, DISCUSSION AND MODELLING

Erosive Wear Behaviour

Figures 2 and 3 display the influence of the relative fibre orientation and the impact-angle and time on the erosion wear of UD-GF/PP. Similar to thermoplastic matrix composites, the maximum weight loss due to erosion was found at oblique impact angles (30°) due to microploughing, plastic deformation and plastic flow indicating that ductile type of erosion dominated [16]. In agreement with earlier observations [16], the results showed a strong dependence of the erosive wear on the relative fibre orientation at low impact angles (30°), but hardly any difference for 60 and 90° impact angles. Furthermore, the material removal was markedly higher in Pa- than in Pe-direction.

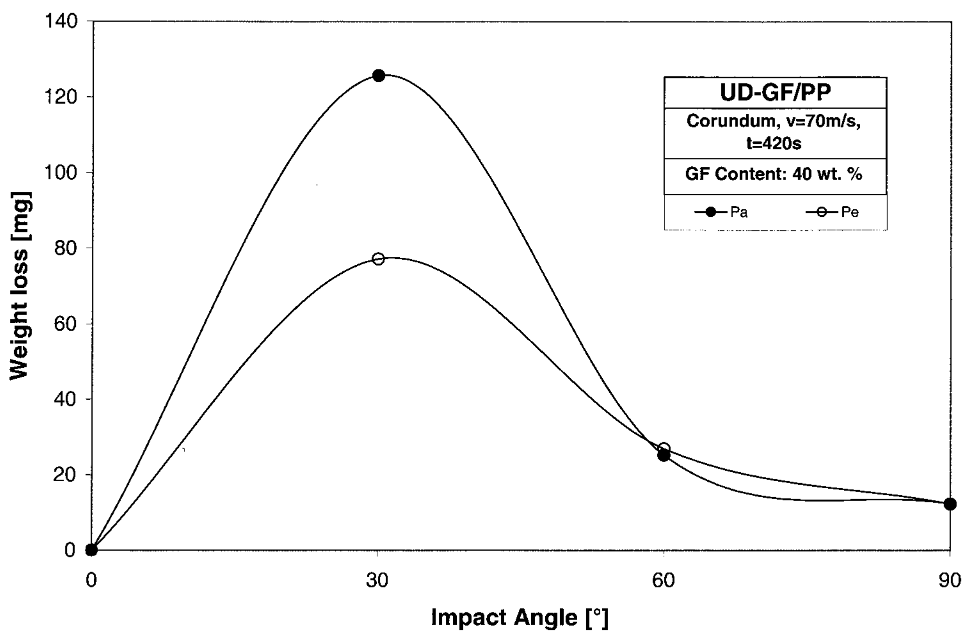

Figure 2. Weight loss variation as a function of impact angle and fibre orientation of UD-GF/PP composites. Note: experimental data present the mean value of 3 erosion tests.

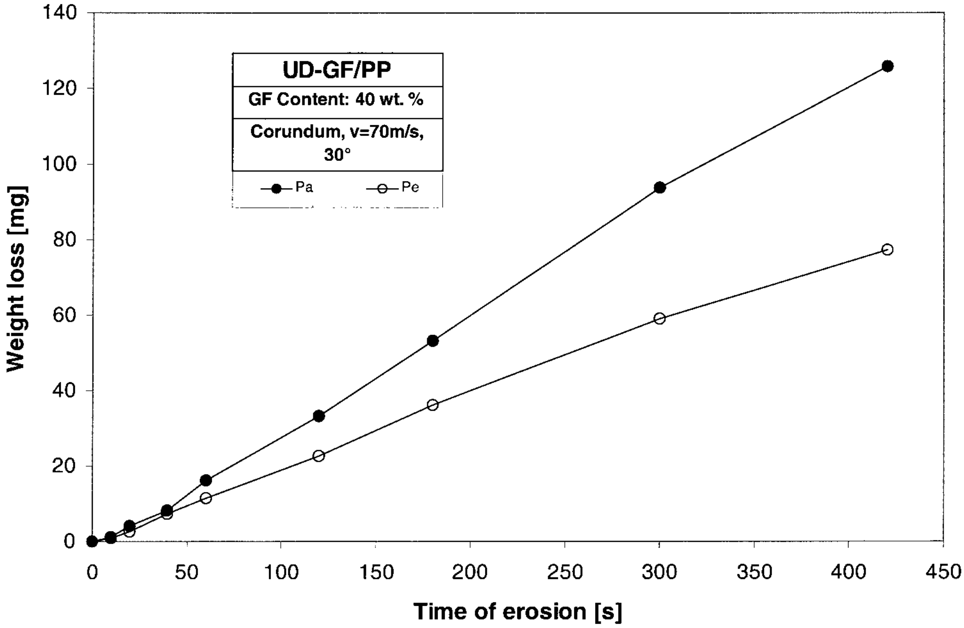

Figure 3. *Weight loss variation as a function of impact time and fibre orientation of UD-GF/PP composites eroded at 30° impact angle. For note cf. Figure 2.*

Dynamic Mechanical Thermal Analysis

DMTA spectra of the UD-GF/PP before erosion are presented in Figure 4. This figure shows the variation of the storage modulus (E′) and that of the loss factor as a function of temperature of the non-impacted material. The storage modulus informs us about the elastic energy storage, whereas the loss factor about the energy dissipation, or damping of this material. The dissipation ability of a material is maximised when the time scale of the deformation is the same as the internal time scale of the material. If the two time scales are substantially different, the energy dissipation is reduced. That is why the absolute $\tan\delta$ value is involved in the calculation of the impact energy threshold beyond which the strength degradation starts (see Appendix).

Tensile Mechanical Characteristics

It has been established that when damage occurs in composite systems, broken fibres reduce the tensile strength whereas delaminations between layers reduce the compressive strength [19–21]. Therefore, the residual tensile strength after solid particle erosion of a UD system may be a good indication of its damage state.

Table 1 provides the experimental values of the tensile strength ratio (σ_r/σ_o, where σ_r = the residual tensile strength after impact and σ_o = the tensile strength of the non-impacted material) after Pa and Pe erosion for different erosion conditions (i.e. time) and thus for different impact energies. It is interesting to note that few seconds of erosion, i.e.,

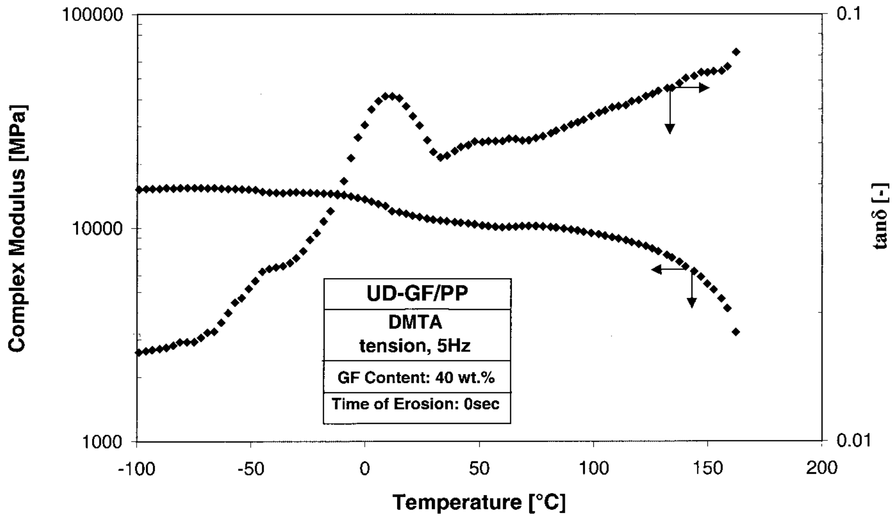

Figure 4. DMTA spectra of the UD-GF/PP before erosion.

Table 1. Experimental values of the tensile strength ratio (σ_r/σ_o) for different impact energies and directions.

			U (J)						
			1.02	**3.06**	**5.1**	**40.8**	**61.2**	**112.4**	**183.6**
UD-GF/PP Pa	$\sigma_o = 430$ MPa	σ_r/σ_o [−]	0.841	0.697	0.684	0.673	0.642	0.658	0.65
UD-GF/PP Pe			0.988	0.807	0.769	0.783	0.78	0.746	0.762

low impact energies, were enough to degrade considerably the tensile strength but the ultimate strength remained relatively high even after long periods of erosion.

Modelling of the Residual Tensile Strength after Solid Particle Erosion

A very recent communication [2] verified the applicability of a semi-empirical approach initially developed by Papanicolau for the prediction of the residual strength after single normal impact also for the solid particle erosion of CF/EP thermosetting composites. The excellent agreement between theoretical predictions and experimental values corroborated the reliability of this model to predict the post impact residual strength of CF/EP showing brittle type of erosion. Because the material removal mechanisms that accompany erosion differ strongly for ductile and brittle type of erosion, it was a great challenge to verify the applicability of the model in a composite system which erodes ductilely.

The theoretical background of this model is analytically described elsewhere [1] while a quick review is presented in Appendix. The model takes into account the inherent material properties, the initial and post-impact tensile strength of the material and the visco-elastic response (viz. mechanical damping) of the non-impacted material. In order to apply this semi-empirical model, three test series are needed. Two tensile tests in order to determine σ_o and σ_∞ and one DMTA test to define $\tan\delta$ of the non-impacted specimen.

Table 2 presents all the characteristics of the UD-GF/PP (Pa and Pe) determined along with energy threshold (U_o) as derived from the model. The values of σ_o, σ_∞ (where $\sigma_\infty =$ the residual tensile strength after high impact time), E_{11} and $\tan\delta$ are experimentally defined, whereas the parameters s and U_o, are calculated (cf. Appendix). Taking into account the U_o values, a comparative study between experimental data and theoretical predictions was carried out. Plotting the tensile strength ratio σ_r/σ_0, versus impact energy, U, (Figure 5), it can be noted that the proposed model holds also for the case of UD-GF/PP as it predicts well both the impact energy threshold and the tensile strength ratio in both erosion directions. The results show that there is a slight difference in the impact energy threshold for Pa and Pe impacts, but there is a clear difference in the ultimate residual strength values. The specimens eroded in Pa-direction maintained 65% of their initial tensile strength while it was 76% for those in Pe-direction. This finding can be explained by comparing Figures 3 and 5. At the beginning of the erosion test the material removal is almost the same for both erosion directions (cf. Figure 3) therefore, the onset of the strength degradation does not differ much. As the specimens are exposed further to erosion, more material is removed under Pa-impact, and therefore the Pa-direction shows a larger tensile strength degradation.

Table 2. Parameters used and derived by applying the proposed model to UD-GF/PP composites.

	σ_o [MPa]	σ_∞ [MPa]	s (–)	m (–)	$\tan\delta$ [–]	V [mm^3]	E_{11} [GPa]	U_o [J]
UD-GF/PP Pa	430	280	0.65	1	0.06	1200	23.5	0.8
UD-GF/PP Pe	430	328	0.76	1	0.06	1200	23.5	1.19

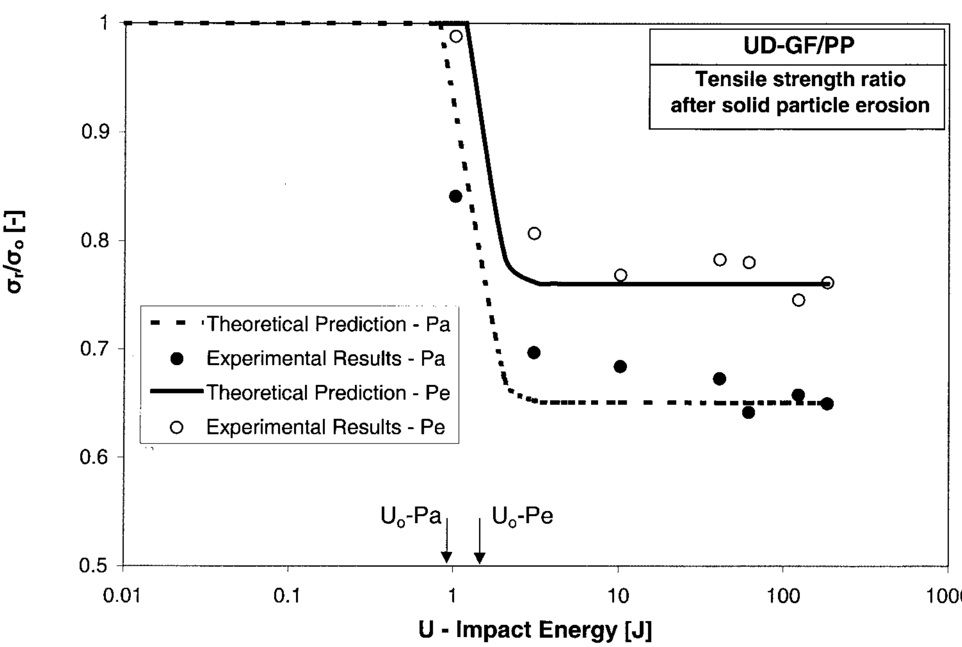

Figure 5. *Experimental values and theoretical prediction of the normalised residual tensile strength, (σ_r/σ_r) of UD-GF/PP due to solid particle Pa- and Pe-erosion as a function of the impact energy (U).*

Comparison of the UD-GF/PP and CF/EP Systems

Figure 6 compares the onset of the strength degradation and the percentage of the tensile strength maintained after solid particle erosion for a typical thermoplastic and thermosetting system, respectively. For the first case, the UD-GF/PP-Pa system was selected while for the latter a cross-ply CF/EP laminate (with 60% fibre volume content) [2], because these systems have shown the most severe tensile strength degradation. The thermoplastic composites presented a very quick onset of the strength degradation, and thus a very low U_o value.

Energy transferred to a material during impact can cause elastic and inelastic deformations depending on the properties of both matrix and fibre material. Strain energy has been pointed out as one of the most significant parameters to improve the properties of the composite [13]. At the same solid particle impact energy, composites of higher capacity for energy dissipation yield less fibre breakage and thus consequently a higher residual tensile strength.

Composites composed of brittle fibre and brittle matrix, such as CF/EP, are unable to undergo gross plastic deformation and so inelastic energy absorbing processes are only involved in cracking [3,7,11]. On the contrary, for thermoplastic composites such as GF/PP, the higher matrix toughness allows substantial plastic deformation which absorbs a great deal of the impact energy [3,11]. Better toughness due to the PP matrix and higher capacity to absorb energy due to GF resulted in a better erosion resistance of the UD-GF/PP system compared to the cross-plied CF/EP.

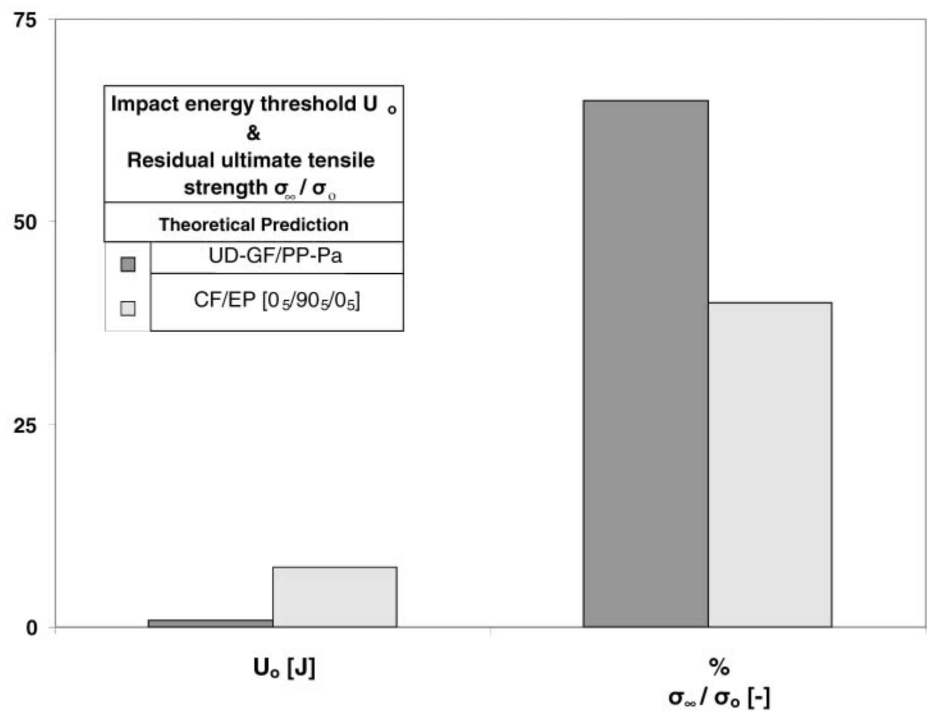

Figure 6. *Comparison of the impact energy threshold (U_o) and the normalised ultimate residual tensile strength (σ_∞/σ_o) after solid particle erosion of GF/PP ($v_f = 20\%$) and CF/EP($v_f = 60\%$) systems*

CONCLUSIONS

Based on the present study devoted to the solid particle erosion of unidirectionally glass fibre reinforced polypropylene, the following conclusions can be drawn:

1. The model proposed for the prediction of the residual strength after solid particle erosion of CF/EP systems holds also for the case of UD-GF/PP at both Pa and Pe erosion directions. The model predicts well both the impact energy threshold and the residual strength after solid particle impact. The proposed model can be used for composites undergoing ductile and brittle erosion. This is quite surprising as very different mechanisms govern the material removal in ductile and brittle erosion.
2. The erosion direction does not influence the onset of the strength degradation, it affects, however, the ultimate residual strength. Erosion in Pa-direction resulted in maximum material removal and maximum loss in the tensile strength.
3. Comparing the response of a ductilely (UD-GF/PP) and brittlely (CF/EP) eroding composite, it was established that the ductile system is more capable to maintain its initial tensile strength, although its tensile strength degradation starts earlier than the brittle CF/EP system.

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APPENDIX

Visco-elastic behaviour of fibre and matrix materials is not the only mechanism for the structural damping in composite materials but appears to be the dominant mechanism in undamaged polymer composites vibrating at small amplitudes. This is also the case in solid particle erosion.

The predictive model used in the present investigation is the result of a series of efforts started in the last decade at Composite Materials Group (CMG), University of Patras and experimentally evaluated in Kaiserslautern [1,2,22–26].

According to this model, the degradation of the mechanical strength due to impact damage is assumed to follow an exponential decay law of the form:

$$\frac{\sigma_r}{\sigma_o} = 1 - e^{-u} \tag{1}$$

where u is a function of the impact energy as well as of the energy absorption capacity of the material expressed through $\tan\delta$. Also, σ_r and σ_o correspond to the residual strength after impact and the corresponding strength of the non-impacted material, respectively.

The model has been developed to cover all impact energy levels and it is not restricted to low impact energies. The two extreme cases which are taken into account in developing the model is the strength of the non-impacted (virgin) material, σ_o, and the residual strength after perforation, σ_∞, after which there is no further degradation of the material due to impact. Thus the strength degradation after impact can be described by a differential equation of the type:

$$s = y + \left[\frac{1-s}{s}\right]\frac{dy}{dx} \tag{2}$$

where, $s = \sigma_\infty/\sigma_o$ = residual tensile strength after high impact (perforation)/tensile strength before impact

$$y = \frac{\sigma_r}{\sigma_o}$$
$$x = \frac{\Delta U}{U_o} = \frac{U - U_o}{U_o}$$

where U is the impact energy and U_o is the impact energy threshold related to the onset of strength degradation. For impact energy values $U \leq U_o$, no interior damage is induced; the impact energy causes the laminate to deform elastically. Once the impactor ceases to exert load on the plate, the latter recovers its original shape and retains its nominal strength in compression/tension.

Solving Equation (2) we obtain:

$$\frac{\sigma_r}{\sigma_o} = 1 - (1-s)\left[1 - \exp\left(-\frac{s}{1-s}\frac{\Delta U}{U_o}\right)\right] \tag{3}$$

From physical considerations, the value of the strength degradation impact energy threshold, U_o, can be calculated by:

$$U_o = U_{\text{elastic}}\frac{\tan\delta}{m(1-s)} = \frac{\sigma_o^2}{2E_{11}}V\frac{\tan\delta}{m(1-s)} \tag{4}$$

where E_{11} is the effective longitudinal Young' s modulus of the laminate; V is the total volume of the specimen; $\tan\delta$ is the loss factor at the T_g of the non-impacted material; m is the mismatching coefficient between adjacent layers due to the difference in their fibre orientation angle [22–26], defined as follows:

$$m = \frac{\sum_{\kappa=1}^{n}(\overline{M_\kappa})_0[Q_{xx,\kappa}(z_\kappa^3 - z_{\kappa-1}^3)]}{\sum_{\kappa=1}^{n}[Q_{xx,\kappa}(z_\kappa^3 - z_{\kappa-1}^3)]} \tag{5}$$

Here $(\bar{M}k)_0$ is the mean value for the bending stiffness mismatching coefficient of the κ-lamina, $Q_{xx,\kappa}$ is the x-direction stiffness matrix term of the κ-lamina, z_κ is the distance of the κ-lamina from the middle plane of the laminate and n is the total number of plies in the laminate. The mean value of $(\bar{M}k)_0$ is defined as follows:

$$(\overline{M_{\kappa-1}})_0 = \frac{(M_{\kappa-1,\kappa})_0 + (M_{\kappa,\kappa-1})_0}{2} \tag{6}$$

where $(\overline{M_\kappa})_0$ refers to κ-lamina and $M_{\kappa-1,\kappa}$ and $M_{\kappa,\kappa+1,}$ refer to the interfaces of the adjacent layers $(\kappa-1)$, κ and $\kappa,(\kappa+1)$.

The above-mentioned m-parameter depends on the laminate material system elastic properties, lay-up, stacking sequence and individual lamina thickness. For the case of UD composites, $m=1$.

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