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Effects of fibre content and relative fibre-orientation on the solid particle erosion of GF/PP composites

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Abstract

The erosive wear behaviour of glass fibre (GF) reinforced thermoplastic polypropylene (PP) composites was studied in a modified sandblasting apparatus as a function of the impact angle (30, 60 and 90°), relative fibre-orientation (parallel Pa and perpendicular Pe), fibre length (discontinuous, continuous) and fibre content (40–60 wt.%).

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. In contrast, the fibre length did not affect the erosive wear behaviour especially at high impact angles.

The inclusion of brittle GF led to higher erosive wear rates (ER) of the GF/PP composites; the higher the fibre content, the higher was the ER. Nevertheless, the composites still failed in a ductile manner. Different approaches proposed to describe the relationship between ER and fibre content were applied. Best results were generally delivered with the inverse rule of mixture. The modified rule of mixtures proposed for abrasive wear do not seem to apply for erosive wear.

Keywords: Solid particle erosion; Impact angle; GF/PP; Fibre content; Rules of mixture

1. Introduction

Polymer composites with both discontinuous and continuous fibre reinforcement possess usually very high specific (i.e. density related) stiffness and strength when measured in plane. Therefore such composites are frequently used in engineering parts in automobile, aerospace, marine and energetics applications. Due to the operational requirements in dusty environments, the erosion characteristics of the polymeric composites may be of high relevance. Erosion tests have been performed under various experimental conditions (erodent flux conditions, erosive particle characteristics) on different target composites. It has been concluded that composite materials present a rather poor erosion resistance [1–10].

A crucial parameter for the design with composites is the fibre content, as it controls the mechanical and thermomechanical responses. In order to obtain the favoured material properties for a particular application, it is important to know how the material performance changes with the fibre content under given loading conditions. The erosive wear behaviour of polymer composite systems as a function of fibre content has been studied in the past [11–13]. It was concluded that the inclusion of brittle fibres in both thermosetting and thermoplastic matrices leads to compositions with lower erosion resistance. Nevertheless, no definite rule is available to describe how the fibre content affects the ER of a composite. An analytical approach was presented by Hovis et al. [14] which presumed that the ER of a multiphase material depends on the individual ER of its constituents. The linear (LROM) and inverse (IROM) rules of mixture were proposed and evaluated for a multiphase AL–Si alloy. The same rules of mixture were adopted by Ballout et al. [15] for a glass-fibre reinforced epoxy composite. These two rules of mixture were also proposed to model the abrasive wear of unidirectional (UD) fibre reinforced composite materials [16,17]. Unlike the erosive wear, the applicability of these rules to the abrasive wear was limited as a steady state process was supposed to hold. To refute this limitation a new model was proposed from Yen et al. [18], who suggested that the abrasive wear behaviour is quasi-steady state in nature. In this study, it was stated that in practice other processes such as reinforcement debonding, reinforcement fracturing and wear scarring (chip removal) beside abrasion are likely to occur in a non-steady state manner. Two mechanisms, each representing the two extremes of the quasi-state wear behaviour (maximum and minimum fibre wear resistance, respectively) were described. A literature survey showed that

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information on the effects of fibre content on the erosive wear behaviour is scarce and its modelling is also limited (mostly studied for thermosetting matrix systems). As different mechanisms of material removal seem to govern the erosion of thermoplastic matrix composites, the main aim of this study was to evaluate whether or not the proposed rules of mixtures can be used for GF/PP composites. It was of interest to investigate how the relative fibre-orientation in UD composites affects the erosion behaviour of these composites. This is particularly interesting as different trends are observed in various studies [1,5,8,9,19,20]. Finally, the effect of the fibre length on the erosive wear behaviour was also a target of this study.

2. Experimental

2.1. Materials

Table 1 lists the composition and designation of the materials tested. In the present study, the PP matrix was reinforced with continuous UD GF (∅ 17 μm) and processed into parts via hot pressing. The PP matrix continued a polymeric coupling agent. Coupling was achieved by adding 5 wt.% of a maleic-anhydride grafted PP (maleic anhydride content ca. 2 wt.%) to the PP during the melt impregnation of GF tows [21]. The fibre weight fraction (wt.%) of the composition varied from 40 to 60 wt.%. The relative densities of GF and PP do not allow to produce composites of higher fibre content. In order to investigate the role of fibre length on the erosive wear behaviour of GF/PP composites, GF/PP compositions with 40 wt.% discontinuous short (S) and long (L) GF reinforcement were also produced. For this purpose the impregnated tows were cut in different lengths (discontinuous S (~2 mm) and L (~10 mm), respectively). From these granules plaques were injection moulded [22]. The erosive wear behaviour of both pure PP and glass (window grade) was additionally examined.

2.2. Testing

All the erosion tests were performed in a commercial sand-blasting chamber (ST 800, Paul Auer GmbH, Mannheim, Germany) equipped with a boron carbide jet nozzle and an air nozzle with internal diameter of 10 and 4 mm, respectively. The erosion apparatus is described elsewhere in details [23]. Sharp, angular corundum particles with a size between 60 and 120 μm and a hardness of 9 (Mohs), 1800/2100 (Knoop) were selected as erodent. The distance between the sample holder and the nozzle was constant (160 mm). The impact angle was adjusted by turning the sample holder. 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 [24]. The eroded area was also constant as a steel cover frame with circular opening was placed on the surface of the specimens. The mass flow of the erodent material perpendicular to the flow axis was measured by collecting and measuring the weight of the erodent gone through the mask having a hole of 30 mm diameter. This corresponded to a 15 g/s mass flow. At an angle of impingement different from 90°, the projection of the specimen surface on the plane perpendicular to the flow axis was smaller. Therefore, lower mass of erodent reached the surface in the unit time. For flat surfaces, the multiplying factor K ($K = \sin\alpha$), has been used for estimation of the erodent flux. At small angles the shadow effect due to the finite thickness of cover plate may influence further the mass flow of the erodent. This effect was marginal for angles higher than 20° for the test geometry used, therefore it has not been taken into account. All erosion tests were performed at room temperature.

The composite weight loss was recorded as a function of erosion time by a precision balance (AT261 Mettler Toledo, sensibility 50 μg). Before weighting, the corundum particles were removed from the specimen surface by air blasting. The erosive wear behaviour was characterised through the weight loss or the ER of the specimen. The ER was defined through the weight loss rate (mg/kg), i.e. the weight loss of the specimen due to erosion normalised by the weight of the erodent causing the loss.

Three impingement angles were selected (30, 60 and 90°). At zero impact angle it was assumed that there was negligible wear because the eroding particles did not practically impact the target surface [25]. There was no meaning to indicate the erosion direction for GF/PP with short (SGF) and long discontinuous fibres (LGF), as the fibres were randomly

Table 1
Designation and composition of the materials tested

Designation	GF		Fibre type	Coupling
	w_f (weight fraction %)	v_f (volume fraction %)		
PP	0	0	–	+
SGF/PP	40	20	S	+
LGF/PP	40	20	L	+
UD-GF/PP40	40	20	UD	+
UD-GF/PP48	48	26	UD	+
UD-GF/PP55	55	32	UD	+
UD-GF/PP60	60	38	UD	+
Glass	–	–	–	–

distributed in the composite. For the UD composites the erodent flux was oriented once parallel (Pa) and once perpendicular (Pe) to the GF.

The eroded surface was inspected in a Jeol (Tokyo, Japan) scanning electron microscope (SEM). The samples were gold-sputtered in order to reduce charging of the surface.

3. Results and discussion

3.1. Erosive wear behaviour (steady state erosion)

3.1.1. Effects of fibre-orientation and length

Erosive wear behaviour can be grouped in ductile and brittle categories, although this grouping is not definitive [9]. Thermoplastic matrix composites show generally ductile erosion while the thermosetting ones erode in a brittle manner. However, there is a dispute about this failure classification, as the erosive wear behaviour depends strongly on the experimental conditions and the composition of the target material (art and relative content of the constituent materials).

Figs. 1 and 2 display the influence of the impact angle, the relative fibre-orientation and the fibre content on the erosion wear of UD-GF/PP. Apart from this aspect, Fig. 3 illustrates the effect of reinforcement length in GF/PP composites with 40 wt.% fibre content. The erosion results are presented in terms of the steady state erosion rate for the sake of comparison with literature data. In Fig. 1a, the weight loss as a function of the impact angle is shown additionally. Note that the difference in the erosion response of the tested composites with different fibre content is more clear at all impact angles if the weight loss instead of the ER is regarded. This is due to the effect of the incubation- and acceleration-periods which is not involved in the steady state ER value. The comparison of Figs. 1b and 2 indicate that a

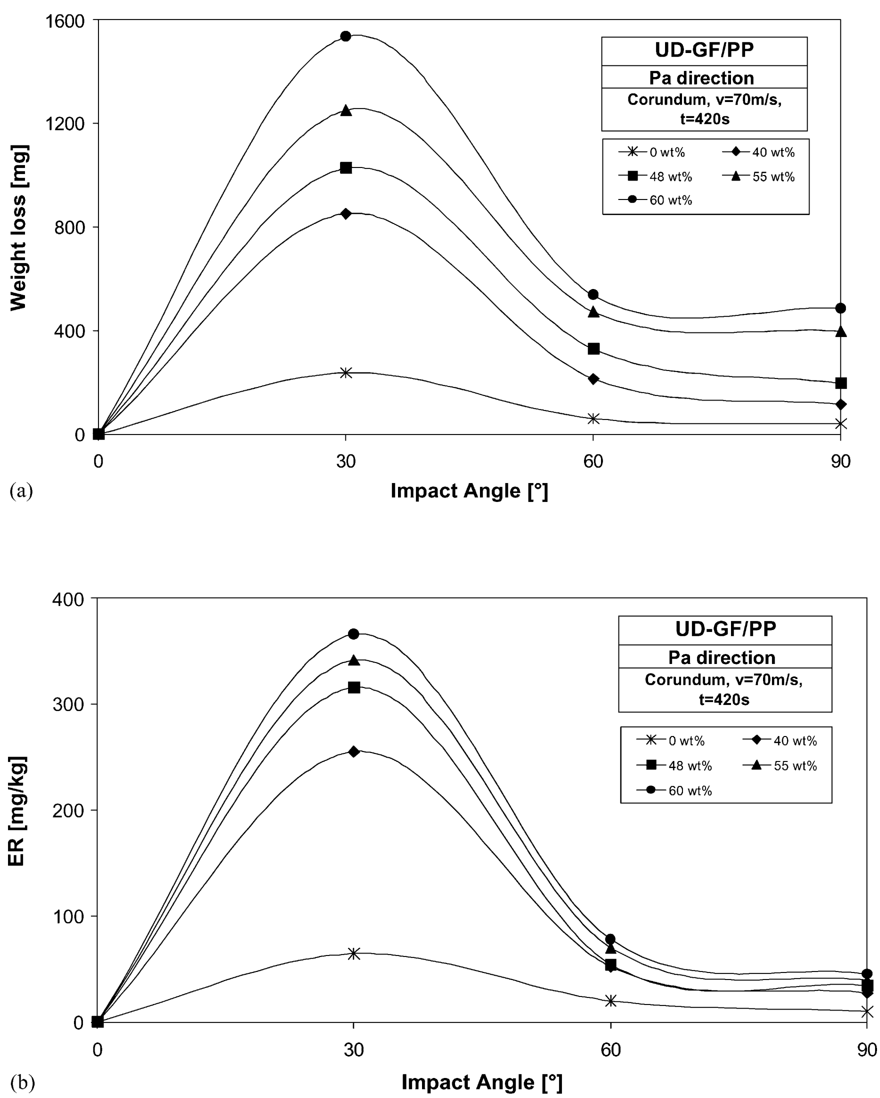

Fig. 1. Weight loss (a) and erosion rate (ER) (b) as a function of impact angle and fibre content of UD-GF/PP composites containing fibres aligned parallel (Pa) to the erosion direction, respectively.

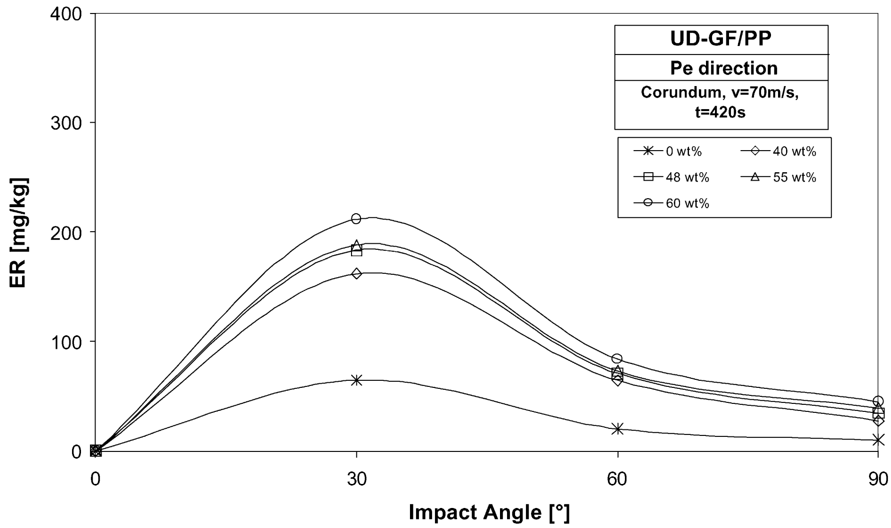

Fig. 2. Erosion rate (ER) as a function of impact angle and fibre content of UD-GF/PP composites containing fibres aligned perpendicular (Pe) to the erosion direction.

strong dependence of the erosive wear exists as a function of the relative fibre-orientation only at 30° impact angle. At 60° oblique impact hardly any difference can be found between the samples impacted Pa and Pe to the fibre direction. Further, there is no sense to indicate the erosion direction at normal impact (90°) because the particles hit the same transverse area. For the UD specimens with fibres aligned Pa to the impinging direction, the erosive wear was considerably higher than that at Pe alignment to the jet. This result holds for all compositions tested and is in agreement with some past observations [9,19] however in contrast to some others [1,5,8,20].

The results in Fig. 3 indicate that there is no difference between SGF/PP and LGF/PP. The ER values of both systems are very close to each other and the evident difference is masked by the experimental scatter. The erosive wear of the composites reinforced by SGF and LGF differs only slightly from that of a UD composite eroded in Pe-direction. This suggests that the mechanism of fibre removal in a composite reinforced with discontinuous, randomly oriented fibres equals with that of an UD composite eroded in the Pe-direction. This is due to the fact that in cases of SGF- and LGF-reinforcement the probability that an erodent particle hits a fibre in Pa-direction is rather small compared to

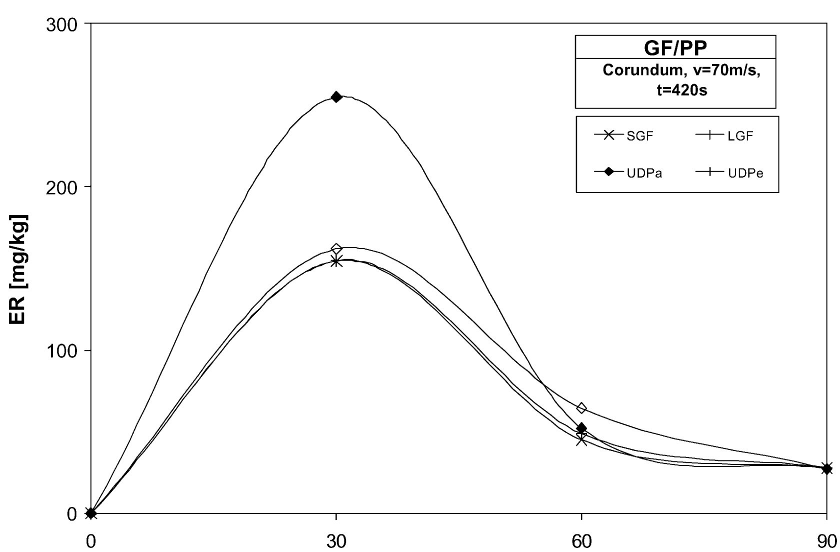

Fig. 3. Erosion rate (ER) as a function of fibre length and fibre-orientation of GF/PP composites at 40 wt.% GF content.

the probability that the particle impacts the fibre oblique. Accordingly when the matrix material is removed, the fibres will be fractured via microbending and removed similarly to the Pe-impact case. In Pa-impact case the fibre fracture and removal demands indentation of the erodent particle on the fibre.

As observed above, the effect of the fibre length or fibre-orientation on the erosive wear decreases as the impact angle moves towards 90°. This can be well explained from the fact that as the impact angle approaches 90° the exposed fibre shape does not change dramatically with a change in the fibre-orientation. Furthermore, the vertical component of the impact force increases, therefore, the energy absorption ability becomes crucial for the erosion resistance of the composite. The ability of a composite to absorb the energy elastically depends more on its fibre content and not on the length or the orientation of the reinforcing fibres.

It is interesting to notice that almost all studies reporting on a better erosion resistance in the Pa-direction refer to thermosetting matrix composites. However, a rather different mechanism governs the material removal process in a thermoplastic matrix composite. The thermoplastic matrix exhibit a ductile erosive wear (plastic deformation, ploughing, ductile tearing) instead of brittle fracture (generation and propagation of subsurface lateral cracks) in a thermosetting resin.

The SEM observations enlightens the results presented above. Fig. 4 illustrates the effect of the relative fibre-orientation on the erosive wear of GF/PP composites. It confirms that for the case of UD-GF/PP with fibres aligned Pa to the impinging direction (Fig. 4a), the erosive wear was greater than for the Pe-direction (Fig. 4b). Under Pa-erosion, the matrix is uniformly grooved and cratered with local material removal (Fig. 4a). Between the fibres which are parallel aligned, the deformation of the matrix material is characterised by ductile flow of the material around the impact site, therefore a ploughing mechanism is encountered. The parallel component of the impact force can make the erodent particles to penetrate into the eroded surface. The ductile flow and the penetration of the erodent in the matrix are hampered by fibres aligned in Pe-direction therefore, the grooves were far less intense (Fig. 4b), and obviously less material was removed in this case.

The following analysis derives an explanation to our experimental results: in the UD composites when the matrix is removed practically nothing remains to support the exposed fibres. Although the fibre fracture is favoured in the Pe-case (due to bending) in our case it is essential to study the matrix removal since all the compositions studied have a large proportion of matrix (40 wt.% matrix corresponds to 62 vol.%). It is intuitive that the matrix can be removed more easily for Pa-direction than in Pe-direction. This is due to the fact that in Pa-direction the matrix is easily ploughed away by the erodents. On the contrary, for Pe-direction the effect of the impact in the matrix is restricted to an area between the fibres. This means that the matrix material is removed faster in the case of Pa-erosion and the GF is strongly exposed to the impinging erodent flux. The exposed fibres are no longer bonded to the composite and are not only removed due to erosion and fracture but also due to the lack of adhesion toward the matrix. Consequently, Pa-direction is more sensitive compared to Pe-direction.

3.1.2. The effect of the fibre content

The variation of the ER with the fibre content was traced to the fibre weight fraction (w_f%). This treatise helped us to apply different rules, proposed in the literature, which are functions of w_f instead of the volume fraction (v_f). The experimental values presented in Figs. 1 and 2 showed that, independently to the impact angle, the ER increased with the addition of brittle GF. An almost linear variation of the ER with the fibre content can be observed until 60 wt.% fibre reinforcement for the three impact angles and for both erosion directions (this variation is implicitly seen in Fig. 5a–c in a logarithmic scale). This indicates that as long as the material removal is dominated from one of the constituents (viz. matrix) a linear variation exists between ER and w_f. However, considering the ER derived from a pure glass sample (see the following paragraph) different thoughts should be made.

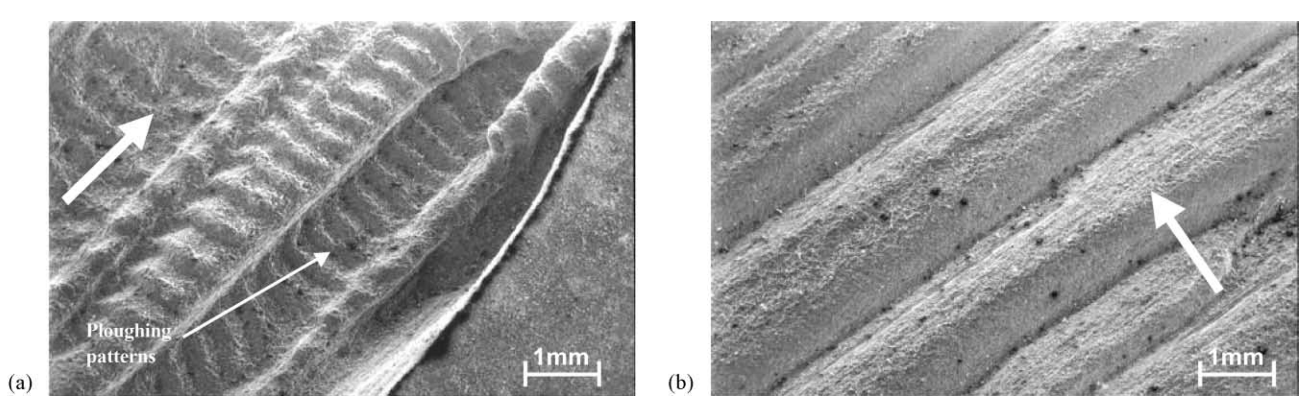

Fig. 4. Scanning electron micrographs taken on the eroded surfaces of GF/PP composites with 40 wt.% fibre content (erosion at 30° angle for 600 s)—illustration of orientation influence on surface topography: (a) parallel (Pa) erosion direction and (b) perpendicular (Pe) erosion direction.

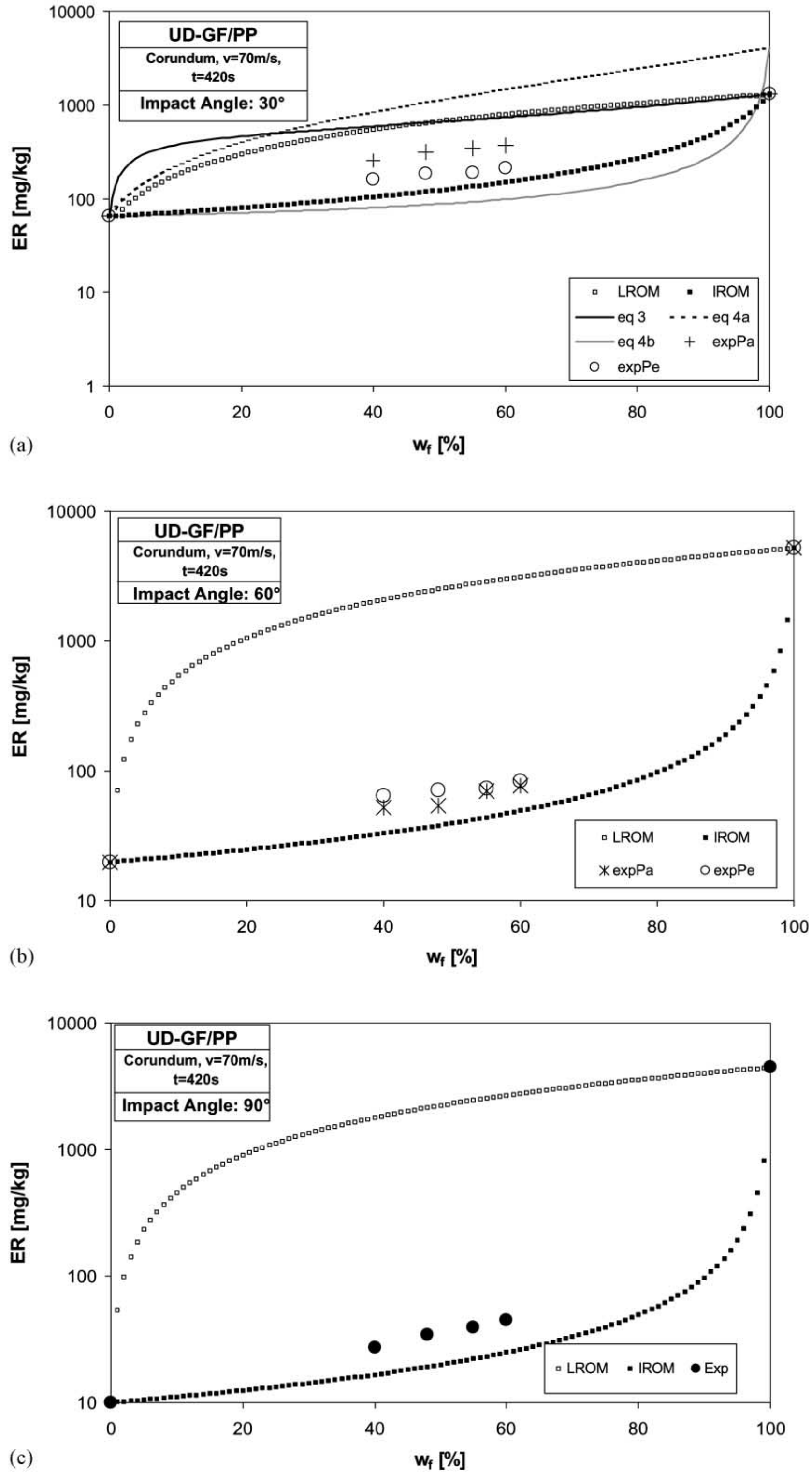

Fig. 5. Application of 'averaging laws of mixture' for the description of the erosion rate (ER) of a composite as a function of the fibre content in the case of a UD-GF/PP composite: (a) 30° impact angle; (b) 60° impact angle and (c) 90° impact angle.

Table 2
Material properties of GF and PP used for the evaluation of the proposed 'averaging rules of mixture'

E_f (GPa)	E_m (GPa)	ER_f (mg/kg)			ER_m (mg/kg)			ρ_f (g/cm^3)	ρ_m (g/cm^3)
		30°	60°	90°	30°	60°	90°		
76	1.2	1300	5196	4448	64	20	10	2.56	0.91

3.2. Modelling the effect of the fibre content on the ER

3.2.1. General considerations: presentation of the various models

Although reports tackling the description of ER as a function of fibre content are scarce and the studied systems do not involve thermoplastic matrix-based systems, different problems and restrictions have already been pointed out and discussed [14,15]. Hovis et al. [14] suggested that the first important factor which should be taken into account is the size of the particle impact damage. If the size of the erosion impact events is larger or comparable with the microstructural size scale, the microstructural constrains should be considered and an 'averaging law' is not applicable. Assuming that the impact size is about 10–20% of the erodent particle size, we can further assume that in our case the impact event is smaller than the microstuctural scale so that the impact events will occur in one of the two phases, viz. PP of GF. Following this analysis we shall try to apply the Eqs. (1) and (2) that express the LROM and the IROM for the case of erosive wear, respectively.

$$\mathrm{ER_c} = w_f \mathrm{ER_f} + w_m \mathrm{ER_m} \quad (1)$$

$$\frac{1}{\mathrm{ER_c}} = \frac{w_f}{\mathrm{ER_f}} + \frac{w_m}{\mathrm{ER_m}} \quad (2)$$

where subscripts c, f and m mean composite, fibre and matrix, respectively, whereas ER and w denote the erosion rate and the weight fraction of the related material.

For the case of erosion at low impact angles (30°) the modified rules of mixture proposed by Yen et al. [18] were evaluated. These rules, which were verified for the case of abrasive wear, take under consideration the modulus of elasticity E_i of the constituent phases, using further a linear and an inverse rule of mixture for the calculation of the E-modulus of the composite.

Modifying the equations for the case of erosion the following forms are obtained:

$$\mathrm{ER_c} = v_m \frac{E_m}{E_c(L)} \frac{\rho_c}{\rho_m} \mathrm{ER_m} + v_f \frac{E_f}{E_c(L)} \frac{\rho_c}{\rho_f} \mathrm{ER_f} \quad (3)$$

with $E_c(L) = v_m E_m + v_f E_f$

$$\mathrm{ER_c} = \frac{E_c(L)}{E_m} \mathrm{ER_m} \quad (4a)$$

and

$$\mathrm{ER_c} = \frac{E_c(I)}{E_m} \mathrm{ER_m} \quad (4b)$$

with

$$\frac{1}{E_c(I)} = \frac{v_f}{E_f} + \frac{v_m}{E_m}$$

where v_i the volume fraction of the respective constituent.

The Eq. (3) refers to the maximum fibre resistance assumption, while (4a) and (4b) to the minimum fibre resistance assumption.

3.2.2. Verification of the various models

Table 2 presents the material properties needed for the verification of the above mentioned equations. The estimation of the ER of the glass was very accurate at 30 and 60° impact angles as a straight linear behaviour was observed. Nevertheless, at 90° impact angle, the glass showed two linear variations. At the beginning of the experiment, a slope similar to that of 60° impact angle was found corresponding to an ER of 4448 mg/kg. After a specific point, a saturation in the weight loss with the mass of erodent was observed, perhaps due to thermal hardening-phenomena. This led to a second, very low slope in the curve and an ER of 70 mg/kg. In the following analysis, the first slope of the curve at 90° impact angle was taken under consideration.

Taking into account the values in Table 2, the experimental data and theoretical predictions were collated. Plotting the ER versus fibre weight content, w_f Fig. 5, different trends can be observed for the three different impact angles. In the case of 30° impact the experimental values for both erosion directions lie between the LROM and the IROM. The LROM seems to be closer to the experimental data for Pa-erosion, while the IROM seems to give a better prediction for Pe-direction. The modified rules of mixture (Eqs. (3) and (4)) proposed for the case of abrasion do not provide a better fitting to the experimental data. The IROM seems to follow the variation of the ER with the fibre weight content in cases of 60 and 90° impact while the LROM largely overestimates the measured ER. The applicability of the LROM in some of the experimental results comes to verify the already existing remark [14], that although generally the IROM predicts better the ER of multiphase systems, when the two constituents are continuous and linear aligned along the incident erodent particle beam direction (UD-GF/PP-Pa, 30° impact), the LROM approach works well.

4. Conclusions

Based on this study performed on the solid particle erosion of GF/PP composites reinforced with discontinuous and continuous GF at various fibre contents, the following conclusions can be drawn.

1. The wear process in thermoplastic matrix composites (GF/PP) presents a maximum ER at 30° impact angle (ductile erosion). There is a slight influence of the fibre length on the erosive wear of GF/PP composites and the role of relative fibre-orientation for UD-GF/PP is evident only at 30° impact angle, where the Pa-direction exhibits the maximum ER. The fibre content seems to influence strongly the ER; the experimental results showed a linear variation of the ER with a fibre content up to 60 wt.%.
2. Different 'averaging laws of mixture' were applied and discussed in terms of impact angle and relative fibre-orientation in respect to the direction of erosion. For all cases, the linear rule of mixture and the inverse rule of mixture seem to provide good bounds in the experimental erosion rates. The modified rules of mixture proposed for abrasive wear do not provide better bounds than those of the LROM and IROM at 30°. Although the abrasive action of the erodent at 30° impact is dominant, the impact action due to the vertical component of the force cannot be any more negligible, especially when the amount of the brittle fibres in the composite is considered.

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