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Fracture behaviour of polypropylene sheets filled with epoxidized natural rubber (ENR)-treated coal gangue powder

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Abstract The morphology, deformation and fracture properties of polypropylene sheets filled with untreated and epoxidized natural rubber (ENR)-treated coal gangue powder (CGP) were investigated by scanning electron microscope (SEM) and the essential work of fracture (EWF) method. The results show that ENR obviously improves the dispersion of CGP particles in the PP matrix and the interfacial adhesion between CGP particles and PP matrix with the well-established interfacial layer. It is found that all composites fracture in a ductile manner as ligament yields completely and crack propagates steadily. The fracture toughness (w_e) of the composites is significantly improved with the complete interfacial layer formed by ENR on the surface of CGP particles. With increasing ENR content, the specific plastic work (w_p) per volume unit of plastic zone of the composites increases considerably in spite of the restricted plastic deformation of plastic zones**.** In Addition, the fracture parameters of different stages of tensile process demonstrate that the positive effect of ENR on the fracture performance of the composites is mainly achieved by notably reinforcing crack resistance at the stage of necking-tearing after yielding.

Introduction

Polypropylene (PP) is one of the most widely-used commercial plastics and the composites with PP matrix are also employed in a variety of applications. Common rigid inorganic particles such as glass beads, calcium carbonate, talc and montmorillonite are often used to improve stiffness and dimensional stability of polyolefin [1–5]. Coal gangue powder (CGP) is generated in the process of coal mining and washing, which is selected as the filler of PP composites in this paper. The main chemical compositions of CGP are silicon dioxide, alumina and other metal oxides, moreover, some organic matters named carbon black analog, are also contained in CGP. Masses of scrap CGP invade considerable amount of farmlands and have potentially negative influences on environment. It may be a meaningful and efficient way to use CGP as reinforcing filler of polymeric materials, however, few attentions have been paid to this field so far.

For the sake of strong interfacial adhesion between rigid particles and PP matrix, proper modifying agent is to be incorporated in. At present, the widely used and effective interfacial modifiers include maleic anhydride grafted polyolefin and elastomers and so forth. [1–3, 6–9]. Compared to typical inorganic particles, CGP is presumed more compatible with PP [10], thus better interfacial adhesion may be obtained between CGP particles and PP matrix. However, the performance of PP/CGP binary composites is not as good as expected [11], indicating that further interfacial modification is still required. Besides, large amount of polar and active groups on the surface of CGP particle, such as hydroxyl, make the interfacial modification possibly more effective.

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Here, epoxidized natural rubber (ENR) was selected as interfacial modifier because the polar epoxy groups bonding on the fundamental chain of ENR are prone to react with the active hydrogen containing groups on CGP surface, like hydroxyl, carboxyl and so on. Otherwise, better dispersion of ENR on CGP surface and stronger interfacial adhesion between CGP particles and PP matrix are to be achieved for the composites containing CGP particles previously treated with ENR latex, compared with directly incorporating the solid ENR in PP/CGP composites.

Till now, few investigations have been carried out on the fracture behaviour of the sheet of PP/rigid particles composites due to the lack of appropriate and valid evaluating methods. In recent years, the rapidly developing essential work of fracture (EWF) method provides a convenient and valid way to evaluate the fracture behaviour of ductile polymer sheets.

The EWF concept [12–17] figures out that the total energy W_f dissipated in the fracture process of pre-cracked body can be divided into two part (Fig. 1). One part is dissipated in inner fracture process zone i.e. essential work of fracture (W_e), which is actually the energy required to form new fracture surfaces and proportional to ligament length l at a given specimen thickness (t), the other is dissipated in outer plastic zone, named non-essential work of fracture (W_p) which is associated with the crazing and shear yielding of the matrix during deformation, and proportional to l^2. So,

$$W_f = W_e + W_p = w_e l t + \beta w_p l^2 t \quad (1)$$

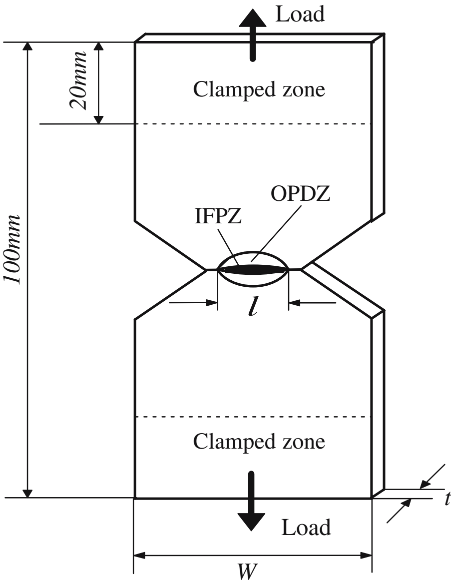


Fig. 1 Deeply Double Edge Notched Tensile (DDENT) specimen used for EWF test

where w_e is the energy dissipated in per ligament area unit, defined as specific essential work of fracture; w_p is the energy dissipated in per volume unit of plastic zone, defined as specific non-essential work of fracture or specific plastic work; β is the plastic zone shape factor. Usually, βw_p is termed as plastic work item which could describe the total plastic work consumption during the deformation. The specific total work of fracture (w_f) dissipated in per ligament area unit can thus be obtained by following equation:

$$w_f = W_f / lt = w_e + \beta w_p l \quad (2)$$

Assuming that both of w_e and βw_p are independent of l, the linear regression line of w_f -l can be determined according to equation (2), and w_e and βw_p can be obtained from the intercept and slope of the regression line, respectively. In addition, the ligament length of the DDENT specimen should satisfy the protocol of the European Structural Integrity Society (ESIS) [18].

In this paper, the ENR-treated CGP filled PP composites were prepared using industrial water-based ENR latex. The microstructures of the composites were studied by scanning electronic microscope (SEM). The EWF method was employed to analysis the influence of ENR content on the fracture toughness and plastic energy dissipation of the composites. The relationships between the microstructure and fracture behaviour of these composites were also discussed.

Experiment

Materials

The block co-polypropylene (K8303: ethylene-propylene copolymer containing 17.8 mol% ethylene) serving as the matrix of the composites was produced by Beijing Yanshan Petrochemical Co., Ltd. (China) with a melt flow rate (measured at 230 °C and 2.16 kg) of 1.39 kg/10 min. The coal gangue powder (CGP) with the maximum particle size of 50μm was provided by Shanxi Coking Coal Group., Ltd. (China). Water-base ENR latex containing 27wt% neat ENR was provided by South China Tropical Agricultural Product Processing Research Institute (China) and the average epoxidizing ratio was 33%.

To achieve strong interfacial adhesion between CGP particles and PP matrix, the following steps were taken. Firstly, the ENR latex was sprayed to the CGP powder and the mixture was kept stirring for a period of time to ensure the homogeneous distribution of ENR on the particles surface. Then the treated fillers were dried at a temperature below 70 °C in an oven to remove the moisture, avoiding the hydrolyzation of epoxy groups at higher temperature. After that, the temperature was raised to 110 °C and kept for about 2 h to promote the interaction between epoxy groups and active groups on the surface of CGP particles. Finally, the dried fillers were ground after being taken out of the oven. The mass ratio of PP to CGP was fixed at 80/20 for the composites, in which the mass ratio of ENR to CGP was set as 0/100 (untreated), 1/100, 2/100, 3/100, 5/100, 7/100, 9/100 respectively.

Specimen preparation

The mixtures described in section 2.1 were extruded on a co-rotating twin-screw extruder (TSSJ-25, Chenguang Chemical Institute, China), with a temperature profile ranging from 160 °C to 210 °C, and the extruded threads were pelletized. After drying, the pellets were injected into both dumb-bell shape and rectangular samples of 4 mm thickness on a (PS40E5ASE, Nissei) precise injection moulding machine, with a temperature profile of 190, 200, 230 and 220 °C from the feeding zone to the nozzle and both the injection and holding pressure of 50 MPa. Some of the injection-moulded samples were compression-moulded into sheets of 0.5 mm thickness at 200°C and 10 MPa. The deeply double edge notched tensile (DDENT) specimens (length × width = 100 mm × 35 mm) were cut from the sheets according to Fig. 1. The pre-cracks were sharpened at the tip of V-type notch on both sides of DDENT specimens using a fresh razor blade, perpendicular to the tensile direction. Before tensile tests, the thickness and ligament length of each specimen were measured using a travelling microscope and a thickness tester respectively.

Fracture tests

The fracture tests were conducted on an Instron (4302) universal test machine equipped with a 500N load cell at a cross-head speed of 5 mm/min, and the test temperature was 23 ± 2 °C. The energy consumed from the onset of loading till specimen failure was calculated from the area of the load-displacement curves. During the test a digital camera was used to record the fracture process.

The compression-moulded sheets of different composites were immersed in liquid nitrogen for about 20 min and then fractured immediately. After sputtering the gold onto the fracture surface to make the samples conductive, the microstructures of the composites were observed using a SEM (JSM-5900LV, JEOL), with an accelerating voltage of 20 kV.

Results and discussions

Fractography

Figure 2 shows the Scanning electron micrographs of the fracture surface of the composites filled with untreated and treated CGP. It can be seen in Fig. 2 (a) that for the untreated CGP filled PP composites, some particles or agglomerates larger than 10 μm in diameter are observed in PP matrix besides numerous small particles, while for ENR treated CGP filled PP composites, the size and quantity of big particles or aggregates decrease with increasing amount of ENR, as seen in Fig.2 (b–d). When the mass ratio of ENR/CGP reaches 7/100, the big particles and aggregates are difficult to observe. This implies that with the surface treatment of ENR, the CGP particles were well dispersed in PP matrix. Additionally it can also be found in Fig. 2 that the interface between CGP particles and PP matrix becomes unclear as ENR content increases, which primarily indicates that ENR could improve the interfacial adhesion between CGP particles and PP matrix.

A closer examination of the fracture surface for the composites filled with untreated and treated particles at a higher magnification (×5000) is presented in Fig. 3. Obviously, there is distinct gap between CGP particle and PP matrix in Fig. 3 (a), however, it is interesting to see some short fibrils linking the particle and PP matrix, which demonstrates that the interattraction between the organic matter on CGP surface and PP matrix may exist, yet the adhesion is still weak, which is responsible for the poor stress transfer from PP matrix to CGP particles. When small amount of ENR is applied to treat CGP (the mass ratio of ENR to CGP is 2/100), the interfacial adhesion between big particles and PP matrix could be partly improved but the effect is not very satisfactory, as confirmed by Fig. 2 (b). With further increase of ENR content, the surface of the big particles is almost encapsulated by ENR layer which contributes to the good adhesion between CGP particles and PP matrix, as shown in Fig. 3 (c) and (d). Simultaneously, at higher ENR content (Fig. 3(c), (d)), some small particles of about 1–2 μm in diameter with regularly spherical shape are observed (marked with the black circles in Fig. 3), whose quantity increases with increasing ENR content. These spherical particles are

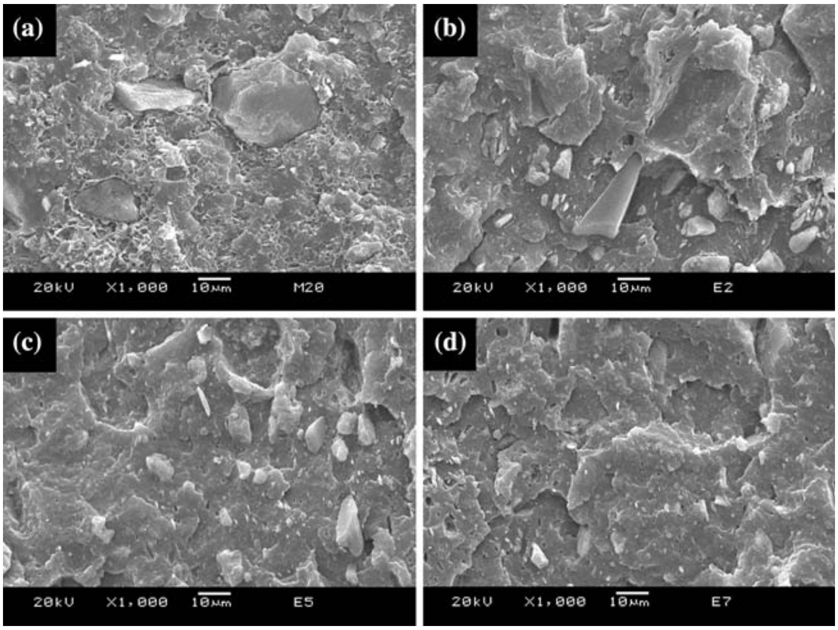


Fig. 2 Scanning electron micrographs of the fracture surface at a magnification of ×1000: (**a**) PP/CGP binary composite, (**b**–**d**) PP/ENR-treated CGP hybrid composites (mass ratio of ENR/CGP:2/100,5/100,7/100 in turn)

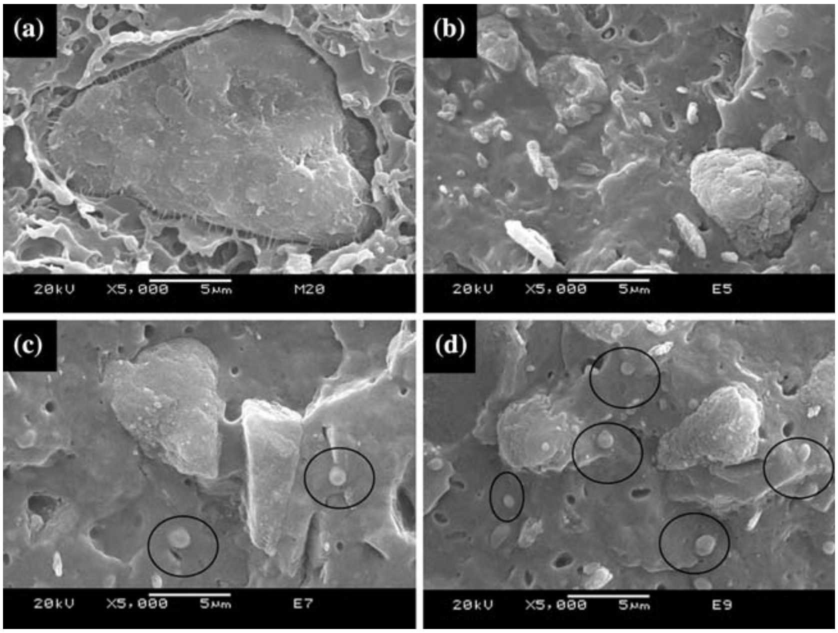


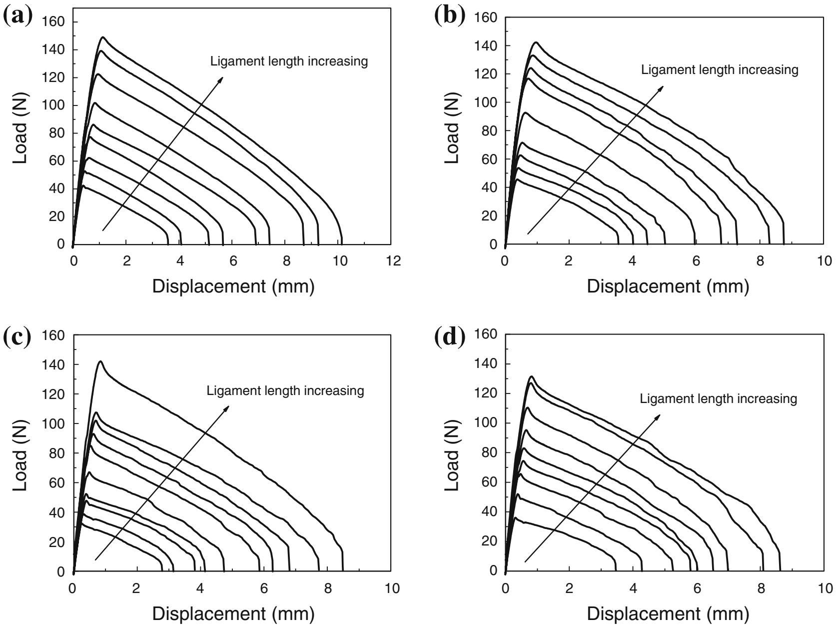
Fig. 3 Scanning electron micrographs of the fracture surface at a magnification of ×5000: (**a**) PP/CGP binary composite, (**b**–**d**)PP/ENR-treated CGP hybrid composites (mass ratio of ENR/CGP: 5/100,7/100,9/100 in turn)

presumed to be ENR particles dispersed in PP matrix or the new-generated particles with core-shell structure containing single or multiple cores, due to the encapsulation of ENR on the surface of small CGP particles. Because of the relatively low ENR content compared with PP matrix, these small spherical particles should be mainly considered as the latter. While in literatures [1, 2, 19], these particles were mainly regarded as elastomer particles and improved the toughness of the composites.

Fracture parameters

Figure 4(a–d) exemplify the load-displacement curves of DDENT specimens during EWF tests for neat PP and the composites filled with untreated and ENR-treated CGP particles. It is obvious that each group of curves exhibits nice self-similarity and reveals the characteristics of complete ligament yielding and stable crack propagation, indicating that ligament length has almost no effect on fracture behaviour of the

Fig. 4 Load-displacement curves for (**a**) neat PP, (**b**) PP/CGP binary composite, (**c–d**) PP/ENR-treated CGP hybrid composites (mass ratio of ENR/CGP:2/100, 7/100)

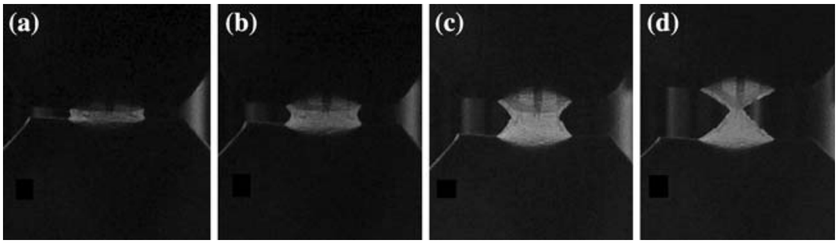


composites and all DDENT specimens fracture in a manner of ductile tearing.

The photographs of fracture process around ligament area also reveal the feature of stable crack propagation of DDENT specimen during the EWF test (Fig. 5). It is seen that with increasing displacement, the crack-tip expands towards the ligament center perpendicularly to tensile direction, and no evidence of necking appears at the crack-tip. All characters described above basically coincide with "post-yielding" phenomenon which ensures the validity of EWF method [20]. Namely, the composites investigated in this paper meet the requirements of EWF method which ensures the reliability of the fracture results [21, 22].

Figure 6 presents the regression lines of w_f -l of neat PP and some composites, showing nice linear relationship proved by the linear regression coefficient (R^2) higher than 0.96. The EWF parameters of all composites are listed in Table 1. The addition of rigid particles in polyolefin matrix usually reduces the fracture toughness of the composites due to the stress concentration triggered by the particles [6]. However, the fracture toughness (w_e) of PP/CGP composite is just a little lower than that of neat PP according to Table 1. This may be caused by the intense overlapping and interacting among stress fields around the particles due to the large quantity of CGP particles and small interparticle distance, which weakens the negative effect of poor interfacial adhesion between CGP particles and PP matrix on the fracture toughness [23]. When CGP is treated by very small amount of ENR (i.e. the mass ratio of ENR/CGP is 1/100~2/100), the fracture toughness of PP/ENR-treated CGP composites decreases sharply, about 30% lower than that of the composites filled with untreated CGP. It is seemed that the filler particles cannot be encapsulated homogeneously by small amount of ENR, which results in decreasing number of stress concentrators and subdued overlapping effect of stress fields. In this situation, the reduction of w_e is unable to be compensated by the increment due to the improved interfacial adhesion, thus the significant decrease of fracture toughness (w_e) is observed. This also coincides with the features of fracture surface in SEM pictures.

Fig. 5 Photographs of the fracture process of DDENT specimens with 11 mm ligament of PP/ENR-treated CGP hybrid composite (mass ratio of ENR /CGP: 5/100)



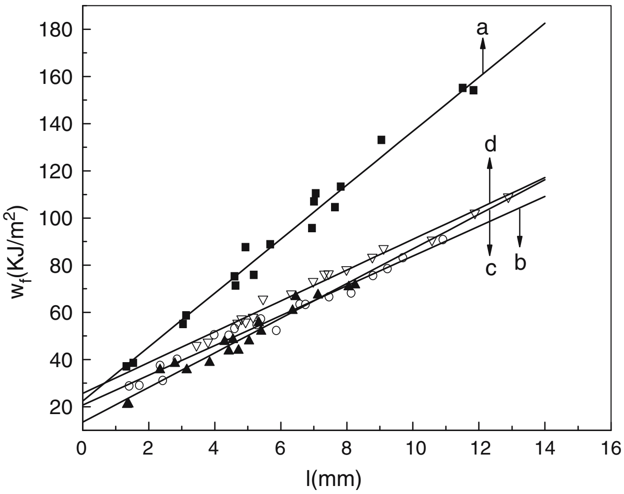


Fig. 6 Plots of w_f –l for (**a**) neat PP, (**b**) PP/CGP binary composite, (**c**)–(**d**) PP/ENR-treated CGP hybrid composites (mass ratio of ENR/CGP:2/100,7/100)

With increasing ENR content, w_e increases gradually. As the mass ratio of ENR/CGP reaches 5/100, the w_e value of ENR-treated CGP filled PP is close to that of untreated CGP filled PP. Combining the SEM results, it is concluded that since the surface of CGP particles is nearly completely covered by ENR, the negative effect of weakened stress field overlapping on w_e can be counteracted by the positive effect of reinforced adhesion on w_e. As the mass ratio of ENR/CGP reaches 7/100, the w_e value of the composite is much higher than that of the composites filled with untreated CGP, and even higher than that of neat PP. It indicates that the CGP particles homogeneously encapsulated by ENR can be strongly bonded to PP matrix, which is in favour of stress transfer and consequentially results in remarkable improvement of crack resistance. The efficient improvement of interfacial adhesion between CGP particles and PP matrix is close related to the particular molecular structure of ENR. The long hydrocarbon segments of the ENR molecular chain are well compatible with PP matrix, whilst the polar epoxy groups have strong physical attraction and even chemical bonding with the active groups, such as hydroxyl group and carboxyl, on the CGP particle surface. It is noticed that near the mass ratio of ENR/CGP up to 7/100, perfect interfacial layer between PP matrix and CGP particles is achieved, corresponding to the best fracture toughness, w_e. With further increase of ENR content (as the mass of ENR/CGP is up to 9/100), the w_e value increases slightly and the excessive ENR mainly forms spherical rubber particles and core-shell structure (see Fig. 3). Thus it can be concluded that the improved interfacial adhesion plays a more important role in elevating the fracture toughness of the composites than the formation of spherical particles. Additionally, different from the interfacial modifier with low molecule weight, the excessive amount of ENR with high molecule weight does not impair the fracture toughness of the composites [6].

Table 1 EWF parameters of all materials studied

ENR/CGP (mass ratio)	w_e (kJ/m^2)	βw_p (MJ/m^3)	R^2 (w_f –l)	β	w_p (MJ/m^3)
0/100	20.72	6.32	0.98	0.266	23.76
1/100	13.16	6.80	0.98	0.223	30.48
2/100	13.53	7.12	0.96	0.240	29.82
3/100	15.66	6.12	0.96	0.198	30.88
5/100	16.42	7.37	0.98	0.210	35.14
7/100	25.69	6.60	0.99	0.200	33.01
9/100	25.83	6.67	0.98	0.201	33.15
Neat PP	21.82	11.57	0.98	0.273	42.37

* Notice: Mass ratio of PP/ coal gangue powder is fixed at 80/20

Plastic work item (βw_p) represents the total energy dissipated for the plastic deformation at the crack tip. It is presented in Table 1 that the βw_p value of untreated CGP filled PP composites is only about 50% of that of neat PP, indicating that CGP particles influence the plastic work consumption severely. Although the influences of ENR content on the variation of βw_p is not obvious, it is evident that the βw_p values of ENR-treated CGP filled PP composites are all higher than that of untreated CGP filled PP composites. According to the relevant researches on fracture behaviour of filled composites, the values of w_e and βw_p can not be elevated simultaneously no matter by changing the amount of rigid filler while fixing the modifier content [24], or changing the amount of both rigid filler and modifier [25]. Moreover, they usually vary in opposite directions. However, in our study it is noticeable that by changing ENR content while fixing the amount of CGP particles, the fracture toughness (w_e) of the composites can be improved, whilst the plastic work consumption (βw_p) does not decrease but even increases slightly. The elevations of both w_e and βw_p were also found in PP/glass beads/SEBS-g-MAH composites by changing SEBS-g-MAH content while keeping the amount of glass beads unchanged [23].

Plastic zone shape factor (β) and specific plastic work (w_p)

The plastic work item (βw_p) is the product of plastic zone shape factor (β) and specific non-essential work of fracture (i.e. specific plastic work w_p), so the variation of plastic work item is affected by both β and w_p. Figure 5 shows the formation of plastic zone of the CGP filled PP composites. When the tensile load is applied to the DDENT specimens, the stress-whitening zones, caused by the density fluctuation caused by crazing and voiding [23, 26], appear at both crack tips immediately. With increasing displacement both the stress-whitening zones expand respectively and then overlap with each other at the center of the ligament, with the height gradually increasing till the failure of DDENT specimens, which results in the formation of complete whitening zone with parabola shape boundary.

Figure 7 shows the plastic zones of the specimens with the same ligament length for different composites. The plastic zone of neat PP specimen can be separated into two parts: intense outer plastic zone (IOPZ) and diffuse outer plastic zone (DOPZ) [27–29] (Fig. 7(a)). The double plastic zone is also observed in PP/CGP composites (Fig. 7(b)), but the IOPZ becomes flatter and the DOPZ becomes less obvious compared to neat PP. This change indicates that CGP particles restrict the plastic deformation of PP matrix by depressing the matrix crazing and voiding. And with the surface treatment of ENR on CGP particles, the plastic zone of the composites is further restrained (Fig. 7 (c–e)).

For the plastic zone with parabola shape the plastic zone shape factor β can be calculated via following equation [27]:

$$h = 3/2\beta l \tag{3}$$

The parameter h is the height of plastic zone. Here the height of IOPZ is taken to replace the height of plastic zone mainly because the energy dissipated in DOPZ is much lower than that of IOPZ [27]. Additionally, it is shown in Fig. 7 that the DOPZ of the composites is rather unconspicuous and its boundary is hard to determine. The curves of h–l for some composites are shown in Fig. 8 and it is obvious that the data points of all composites exhibit fine linear relationship which ensures the precision of the β values. The β values determined by the slope of regression lines are also listed in Table 1. As shown in Table 1, the β value of PP/untreated CGP composite is a little lower than that of neat PP, and with increasing ENR content, the β values of the composites continuously decrease, which is consistent with the variation of plastic zones shown in Fig. 7, while the w_p value of the composite filled with untreated CGP is dramatically reduced (nearly 40%) compared to neat PP, indicating that the addition of untreated CGP depresses the plastic energy dissipated in per volume unit of plastic zone. However, for all PP composites filled with ENR-treated CGP, the w_p values are much higher, especially when sufficient amount of ENR forms a complete interfacial layer between PP matrix and CGP particles, the w_p value is nearly 50% higher than that of the untreated CGP filled PP composite. It indicates that the formation of ENR interfacial layer effectively strengthens the bonding between PP matrix and CGP particles, which blocks the motion of PP molecules and thus leads to more plastic energy consumption per unit volume in plastic zone. And the positive effect of ENR on w_p are capable of counteracting its negative effect on β, thus the βw_p values show a certain degree of increase.

Fracture behaviour before and after yielding

For better understanding of the fracture behaviour of the composites at different stages of fracture process and the influences of interface modification by ENR on the fracture behaviour, W_f is partitioned into two parts via drawing a perpendicular line from the yield point of the load-displacement curve to the abscissa axis. One is the energy dissipated before yielding i.e. $W_{f,y}$ which is contributed to ligament yielding actually, the other is dissipated after yielding i.e. $W_{f,n}$ which is contributed to ligament necking and tearing [28, 30, 31].

Accordingly, following equations are given:

$$w_f = w_{f,y} + w_{f,n} = w_e + \beta w_p \tag{4}$$

$$w_{f,y} = w_{e,y} + \beta' w_{p,y} l \tag{5}$$

$$w_{f,n} = w_{e,n} + \beta'' w_{p,n} l \tag{6}$$

where $w_{e,y}$ and $w_{e,n}$ are the specific essential work of fracture before and after yielding respectively, $\beta' w_{p,y}$

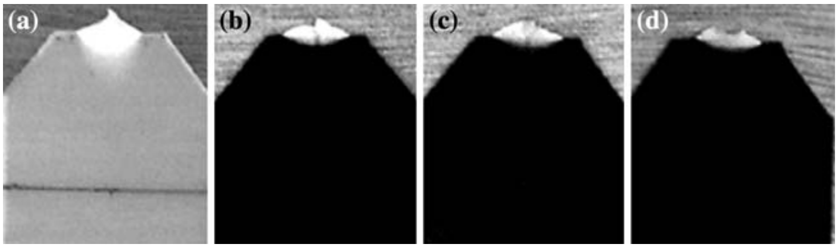


Fig. 7 Photographs of fractured DDENT specimens with 11 mm ligament of neat PP, PP/CGP binary composite, PP/ENR-treated CGP hybrid composites (mass ratio of ENR/CGP: 3/100,7/100), labelled (**a**), (**b**), (**c**), (**d**) in turn

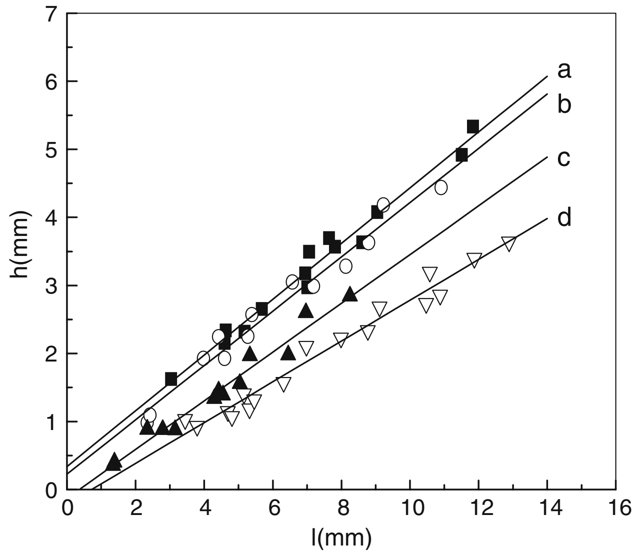


Fig. 8 Plots of *h–l* for (**a**) neat PP, (**b**) PP/CGP binary composite, (**c–d**) PP/ENR-treated CGP hybrid composites (mass ratio of ENR/CGP: 2/100, 7/100)

and $\beta'' w_{p,n}$ are the corresponding plastic work item respectively.

Figure 9 shows the $w_{f,y}$-*l* and $w_{f,n}$-*l* curves of neat PP, PP/untreated CGP composite and PP/ENR-treated CGP composites, which exhibit nice linear relationship, and the fracture parameters determined by the curves are listed in Table 2.

It is found in Table 2 that the fracture parameters of yielding are much smaller than those of necking and tearing for each composite, indicating that the fracture work is mostly dissipated at the stage of necking tearing after yielding. The variation of $w_{e,y}$ values exhibits an inconsistent trend with w_e values, that is, though $w_{e,y}$ values of the composites firstly decrease and then increase with increasing ENR content, they are still lower than that of the untreated CGP filled PP composites, even when the interface layer has been well established. However, the variation trend of $w_{e,n}$ values is very similar to w_e values with increasing ENR content. With the complete formation of the interfacial layer, the $w_{e,n}$ value of the hybrid composites is 40% higher than that of the untreated CGP filled composites, which distinctly indicates that the effect of ENR on the modification of PP/CGP composites, namely to improve the interfacial adhesion between CGP particles and PP matrix, is mainly achieved by significantly improving the crack resistance at the stage of necking-tearing after yielding.

The variation of $\beta' w_{p,y}$ and $\beta'' w_{p,n}$ values are similar with βw_p values, both of which are not very sensitive to the variation of ENR content, indicating that the parallel influences of ENR on plastic deformation before and after yielding.

Conclusions

The fracture behaviour of PP/ENR-treated CGP composites are evaluated by EWF method validly because of the ductile fracture, and the variation of ENR content does not change the fracture mode of the composites. The main influencing factors on fracture toughness of the composites are the overlapping and interaction among the stress fields triggered by CGP particles (stress concentrators) and the interfacial adhesion between PP matrix and CGP particles. When small amount of ENR is used, the incomplete interfacial layer depresses the overlapping effect of the stress fields, resulting in decreased fracture toughness. With the complete encapsulation of ENR on the surface of CGP particles, the interfacial adhesion between PP matrix and CGP particles is effectively reinforced so that the fracture toughness of the composites is elevated significantly about 25% and 20% compared to the untreated CGP filled composite and neat PP, respectively.

The double plastic zone is observed in all the composites studied, and the plastic deformation is restricted by both the untreated and ENR-treated

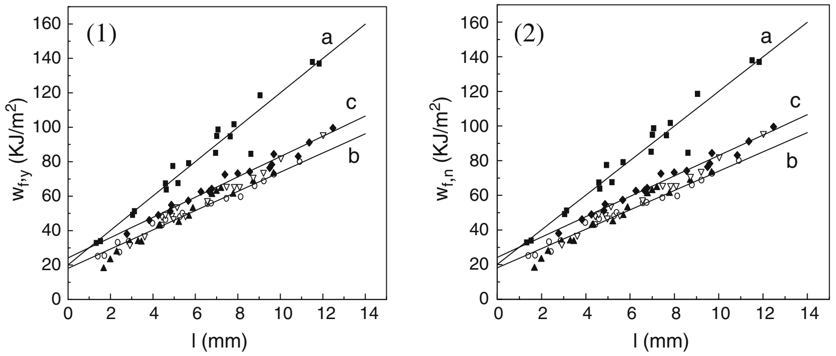


Fig. 9 Plots of $w_{f,y}$–*l* and $w_{f,n}$–*l* for (**a**) neat PP, (**b**) PP/CGP binary composite,(c) PP/ENR-treated CGP hybrid composite(mass ratio of ENR/CGP:5/100)

Table 2 EWF parameters of different stages of fracture process (before and after yielding) of all composites studied in this paper

ENR/CGP (mass ratio)	$w_{e,y}$ (kJ/m^2)	$\beta' w_{p,y}$ (MJ/m^3)	R^2 ($w_{f,y} - l$)	$w_{e,n}$ (kJ/m^2)	$\beta'' w_{p,n}$ (MJ/m^3)	R^2 ($w_{f,n} - l$)
0/100	2.79	0.75	0.93	17.93	5.57	0.98
1/100	2.09	0.66	0.91	11.07	6.83	0.98
2/100	1.94	0.66	0.90	11.59	6.68	0.95
3/100	1.84	0.66	0.98	13.82	5.52	0.95
5/100	0.69	0.85	0.96	15.72	6.51	0.98
7/100	1.08	0.79	0.96	24.61	5.74	0.98
9/100	1.67	0.70	0.97	24.16	5.88	0.98

* Notice: Mass ratio of PP/coal gangue powder is fixed at 80/20

CGP particles. The plastic zones are much flatter compared with neat PP, and the DOPZs become especially hard to observe. Simultaneously the reinforced interfacial adhesion due to increasing ENR content causes a marked improvement of the crack resistance at the stage of necking-tearing, while the plastic behaviour is not affected considerably.

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