Basic functionalization of polypropylene and the role of interfacial chemical bonding in its toughening*

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A reactive polypropylene (PP) containing oxazoline functional groups was prepared by the melt grafting of 2-iso-propenyl-2-oxazoline onto a PP homopolymer and used to introduce varying amounts of interfacial chemical reaction in PP/acrylonitrile-*co*-butadiene-*co*-acrylic acid rubber (NBR) blends. A technique has been successfully developed to control the rubber particle sizes of PP/NBR blends such that various PP/NBR blends with the same rubber particle size can be obtained by using different combinations of processing conditions and the amount of interfacial reaction. It has been found that moderate levels of interfacial chemical bonding are required for a transition from a brittle to ductile failure to be observed in PP/NBR blends. Blends without any interfacial chemical bonding showed no improvement in impact energy whereas up to a 13.5-fold improvement in impact energy (notched Charpy test) was observed for reactive blends above the brittle–tough transitions.

(Keywords: blends; toughening; interfacial bonding)

INTRODUCTION

Rubber particle size and rubber/matrix adhesion are two important factors determining the impact properties of rubber-toughened plastics. In various studies it is noted that a maximum or optimum rubber particle size is preferred for good toughening. In recent studies conclusions have been drawn on whether interfacial chemical bonding is also necessary in addition to a rubber domain size criterion. These two factors are, however, usually interrelated as a result of the complex dynamics of the blend preparation process. It is difficult to alter the dispersed phase size without simultaneously altering blend composition, the amount of interfacial chemical bonding, and/or the molecular weights of blend components, etc. More specifically, it is difficult to prepare families of polymer blends with and without interfacial chemical bonding which have overlapping ranges of rubber domain sizes.

Rubber-toughened polymers may be classified into two broad categories, brittle and pseudoductile, according to the chain flexibility and entanglement density of a polymer[1]. Brittle polymers such as polystyrenes (PSs) and poly(methyl methacrylate)s (PMMAs) have stiff polymer chains and are toughened mainly by increased crazing. Pseudoductile polymers such as polyamides (PAs) and polypropylenes (PPs) have more flexible polymer chains and are toughened by mechanisms mainly involving delocalization of shear yielding in the matrix and rubber particle internal cavitation. Strong interfacial adhesion is generally believed to be required for toughening a brittle polymer, while the role of interfacial chemical bonding in toughening a pseudoductile matrix polymer is not as clear. In toughening a PA, Wu[2] suggested that Van der Waals attraction gives sufficient adhesion for toughening and that interfacial chemical bonding is not necessary. Furthermore, Borggreve and Gaymans[3] concluded that the amount of copolymer ethylene–propylene–diene (EPDM)-*g*-PA coupled at the interface of a PA toughened with EPDM has little influence on the impact behaviour of nylon–rubber blends. By contrast, Angola *et al.*[4] suggested that the toughening of PA blends with styrene–acrylonitrile copolymer via reactive blending did not result from particle size reduction but rather from an interfacial adhesion effect. Despite the above suggestions, there has been no direct experimental evidence on the role of interfacial chemical bonding on toughening independent of particle size.

In an earlier study[5], the role of interfacial chemical bonding has been determined for a rubber-toughened *brittle* polymer system. It was found that high levels of interfacial chemical bonding are required for the effective toughening of PS and, more importantly, that the impact energy of a PS blend increases with the increasing amount of interfacial chemical bonding with the same rubber particle size.

The overall objectives of this study were to investigate the effect of processing parameters and interfacial chemical reaction on the morphology and thus, on the impact properties of rubber-toughened *pseudoductile* PP and to determine the role of interfacial chemical bonding on rubber toughening independent of rubber particle size.

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EXPERIMENTAL

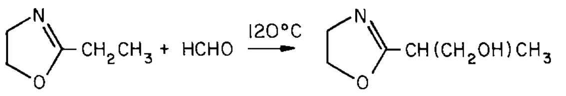
Materials

The rubber used was Krynac X7.50 (formerly Krynac 221) nitrile rubber obtained from Polysar Co. It is a terpolymer of acrylonitrile–butadiene–acrylic acid with a composition of 27:66:7. The acrylic acid provides the necessary functionality for reactive blending and the acrylic acid reactive groups were in large excess compared to its co-reactive group. The weight-average molecular weight was 3.1×10^5 g mol^{-1}.

The PP was a non-reactive homopolymer obtained from Shell (GE6100). It had a melt flow index of 1.0 dg min^{-1} (ASTM D1238, 230°C and 2.16 kg). A reactive PP was prepared by the melt grafting of 2-iso-propenyl-2-oxazoline, synthesized from 2-ethyl-2-oxazoline, onto the homopolymer. The functionalized PP had a melt flow index of 14 dg min^{-1} (ASTM D1238, 230°C and 2.16 kg) and 0.19 wt% oxazoline as characterized by n.m.r. spectroscopy. The oxazoline-grafted PP was purified and blended with the homopolymer PP in desired proportions so as to control the amount of oxazoline in the PP matrix, and thus the amount of interfacial reaction. The molecular weight of the grafted PP was significantly lower than the homopolymer PP as a result of chain scission during grafting. However, the molecular weight drop did not present a problem because the grafted PP was only used in limited concentrations in the matrix phase having minimal effects on impact properties and the impact energies reported for the blends were always normalized with the impact energies for their corresponding matrices.

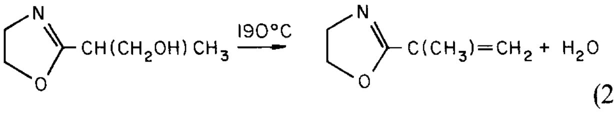
Synthesis of 2-iso-propenyl-2-oxazoline

In a typical synthesis operation, 500 g of analytical grade 2-ethyl-2-oxazoline was mixed with 160 g of analytical grade paraformaldehyde (molar ratio 1:1.05) in a 1 l flask equipped with a condenser and a thermometer. The mixture was heated up to 120°C in a silicon oil bath while a highly exothermic reaction occurred with the temperature rising to ~160°C. The reaction mixture was allowed to cool down and was maintained at 120°C for 5 h with stirring. A condensation product was formed at this stage[6].



(1)

The apparatus was then converted to a distillation device and the temperature of the reaction mixture raised to 190°C at which point dehydration occurred to give 2-iso-propenyl-2-oxazoline.



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Distillates between 110°C and 145°C were collected and dried twice with solid sodium and filtered. The filtered product was redistilled and distillates between 140°C and 145°C were collected. The overall yield was ~15%. The final product was characterized by Fourier transform infra-red (*FT*i.r.) spectroscopy using a Bomem MB-120 *FT*i.r. spectrometer.

Melt grafting of 2-iso-propenyl-2-oxazoline onto PP

The melt grafting of 2-iso-propenyl-2-oxazoline onto the PP homopolymer was carried out at 190°C and 100 rev min^{-1} on a Haake Rheocord 600 batch mixer equipped with roller blades. A peroxide initiator, Lupersol 130, a 90% solution of 2,5-dimethyl-2,5-di-(t-butylperoxy)-3-hexyne with a half-life of ~1.5 min at 190°C was used as received (Lucidol Division, ATOCHEM North America). In a typical grafting process, 0.22 g of the initiator was mixed with 3.0 g of the monomer and the mixture was added to 44 g of solid PP. The wet mixture was then fed into the preheated Haake mixer and allowed to react for 5 min. The reaction product was removed from the mixer and dissolved in refluxing toluene at a concentration of ~4 wt/vol%. The solution was precipitated into seven volumes of methanol, filtered, washed, and dried in vacuum at 75°C for 48 h. The purified product was characterized using both *FT*i.r. and n.m.r. spectroscopy (Bruker 400 MHz n.m.r. spectrometer).

Preparation of PP/NBR blends

PP/NBR blends were prepared in the same Haake mixer as used for grafting. Throughout this work, the same NBR rubber was used for both reactive and non-reactive blends and the rubber phase content was kept constant at 20 wt% in all blends. The rubber particle size was varied by changing either the processing conditions (with temperature the most important one) and hence the viscosity ratio between the phases or the amount of interfacial reaction or both.

The relative viscosities of the two phases were determined from the torques required to process each following the approach of Favis and Chalifoux[7]. The steady-state torques required to melt process both the rubber phase and the PP matrix individually were measured at similar processing conditions as those used to prepare the two component blends. The torque ratios, T_R, between the rubber phase and the matrix were calculated for each blending condition:

$$T_R = \frac{\text{steady-state torque of rubber}}{\text{steady-state torque of matrix}} \tag{3}$$

The torque ratio was combined with the specific energy input during melt blending into a single factor called the processing parameter, P_p, defined as:

$$P_p = \frac{\text{specific energy input}}{\text{torque ratio}} \tag{4}$$

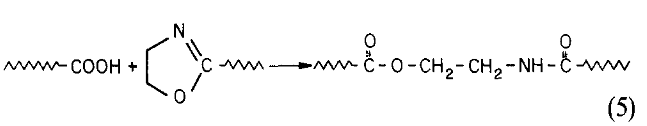
The specific energy input was obtained by multiplying the integral of the area under the blending torque curve as a function of time by mixing speed per unit mass of blend ingredients. The processing conditions used to prepare PP/acrylonitrile-*co*-butadiene-*co*-acrylic acid

Table 1 Torque ratio, T_R, and processing parameter, P_p, values for different processing conditions in PP/NBR blends

Temperature (°C)	Rotor speed (min^{-1})	Mixing time (min)	T_R	P_p (J g^{-1})
266	144	1.0	5.1	5.4
224	98	2.0	3.0	16
195	98	4.0	1.9	50
175	74	7.0	1.2	140
166	50	12.0	0.7	622

rubber (NBR) blends and their corresponding T_R and P_p values are summarized in *Table 1*.

Blends containing varying degrees of interfacial reaction were obtained by varying the proportion of the functionalized PP in the PP matrix. The interfacial reaction between the oxazoline group on the PP backbone and the carboxylic acid group (in large excess compared to the oxazoline group) on the NBR backbone was earlier documented by Baker and Saleem[8]. During melt blending, the rubber molecules are grafted onto the matrix phase by a coupling reaction between the two reactive groups to form an amido-ester linkage.



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Measurement of rubber particle size

The rubber particle size was determined by scanning electron microscopy (SEM). Samples from the blender were fractured under liquid nitrogen and etched in 1 M chromic acid at 70°C for 10 min to remove the rubber phase. The etched surfaces were vacuum coated with gold and observed on a Jeol 840 microscope. At least three images, each with 100–500 particles, from different specimens were taken for each sample and analysed on a Vidas image analysis system to obtain number average particle sizes (D_n). While some variation in particle shape was observed from sample to sample, the volume average particle size (D_v) was found to be 3- to 3.5-fold larger than D_n for all examples. Since the ratio of D_v/D_n remains the same over a wide range of particle sizes the values of D_n were used in all correlations[9].

Impact tests

Both notched Charpy and unnotched disc type tests were done using a Rheometrics RDT-5000 instrumented falling weight impact tester.

The notched impact properties were measured in conformance with the requirements of ASTM D256. Standard Charpy specimens (127 × 12.7 × 6.35 mm) were injection moulded at 230°C and a notch of 0.25 mm radius and 45° angle was machined on all specimens using a multiple tooth rotating cutter and air cooling. Charpy impact tests were carried out at a speed of 1.0 m s^{-1} at 23°C. Ten specimens were tested for each sample. The mean impact energies and standard deviations were obtained (the error bars in the figures represent 2σ). Normalized impact energies, i.e. those of blends divided by those of their references, were reported. Pure PP was used as the reference for non-reactive blends while, for reactive blends, the same compositions as in blend matrices but without any rubber were used as references. A ductility index was defined as the ratio of energy absorbed after the maximum force to total energy and calculated as:

$$\text{ductility index} = \frac{\text{total energy} - \text{energy up to maximum force}}{\text{total energy}} \tag{6}$$

Unnotched disc-shaped specimens (3.2 mm thick) were injection moulded at 230°C. The disc specimens had a diameter of 37 mm and were 3.2 mm thick. The impact tests were carried out at 7.6 m s^{-1} at 23°C. A minimum of 25 tests were done for each sample and the mean impact energies and standard deviations were obtained. Normalized impact energies (matrix as reference) were reported.

RESULTS AND DISCUSSION

Functionalization of PP

There are no known commercially available PPs having basic reactive groups. Thus the functionalization of PP became a part of this research project. Although there have been recent efforts in this laboratory to graft aminomethacrylate-type monomers onto polyolefins[10], their reactions during melt blending have not been studied in depth. On the other hand, the reactions between oxazoline and carboxylic acid in the melt have been well documented[8]. Therefore, 2-iso-propenyl-2-oxazoline was chosen as the monomer to be melt grafted onto the PP.

The synthesized monomer was characterized using *FT*i.r. spectroscopy (*Figure 1*). The spectrum shows a strong band at 1611 cm^{-1} characteristic of the double bond, and a weaker band at 1659 cm^{-1} characteristic of the oxazoline structure. After the melt grafting process, the strong band at 1611 cm^{-1} characteristic of the monomer (double bond) disappeared from the *FT*i.r. spectrum of the grafted PP (*Figure 2*) while a band at 1658 cm^{-1} characteristic of the oxazoline ring was present, confirming the grafting. ^{1}H n.m.r. spectroscopy (*Figure 3*) of the purified product in deuterated toluene solution was used to determine the percentage of grafting by calculating the ratio of the integral of peaks at ~3.55 and 3.80 ppm (for the four hydrogen atoms on the

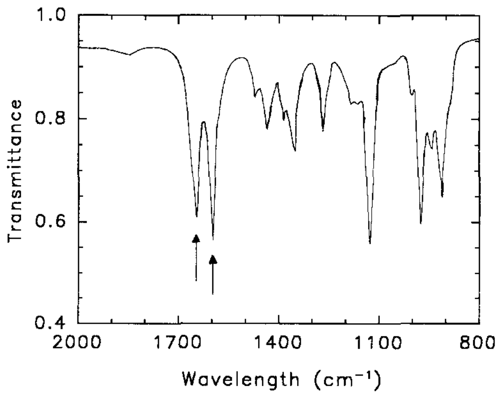


Figure 1 *FT*i.r. spectrum of 2-iso-propenyl-2-oxazoline

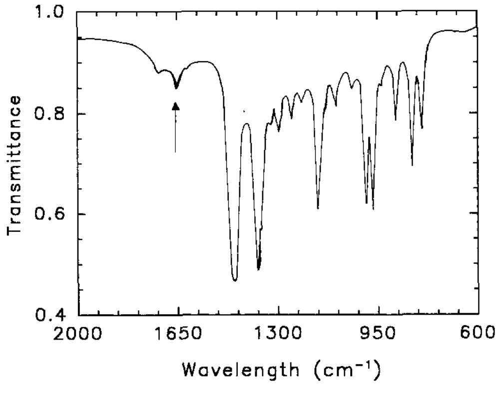


Figure 2 *FT*i.r. spectrum of oxazoline grafted PP

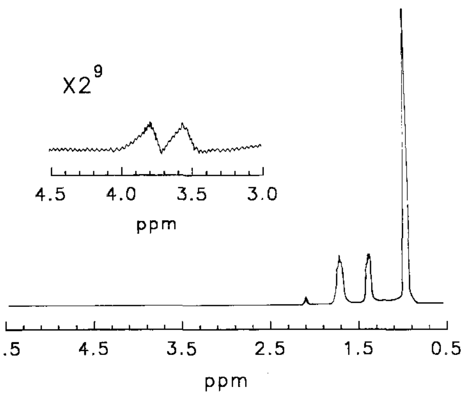


Figure 3 ^{1}H n.m.r. spectrum of oxazoline grafted PP

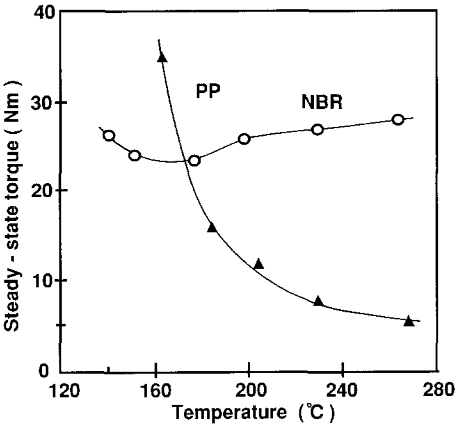
oxazoline ring) to the integral of peaks between 0.5 ppm and 1.8 ppm (for the six hydrogen atoms of PP). The result was 0.19 wt% grafting. *F*Ti.r. examination of the filtrate from purification showed only a little low molecular weight PP and oxazoline homopolymer. Most of the unreacted monomer was easily recovered (a small amount of monomer was lost during the grafting process due to vaporization). The absence of homopolymer of the grafting monomer has been shown to indicate that monomers are grafted on as single oxazoline units on the PP chain and not as long branches[11]. While the percentage of grafting (0.19 wt%) could have been increased using different grafting conditions it was kept low in this study so that it would be completely miscible in the PP matrix.

Influence of P_p *and interfacial reaction on particle size*

For non-reactive blends without any interfacial reaction, the morphology could be controlled over a wide range because of the convenient rheological behaviour of the PP and NBR. This is illustrated in *Figure 4*. While PP showed a substantial drop in steady-state torque with increasing temperature the NBR showed little decline (all measurements taken at the same rev min^{-1} and hence shear rate as used in blending). The steady-state torques were very reproducible with the exception of those for the PP between 166°C and 175°C where the variation was ±10%. It is suspected that some undetected temperature increase occurred in this range. By changing temperature the torque ratios could be varied from 5.1 at high temperature to 0.7 at low temperatures (*Table 1*). The torque ratio was found to be the unique parameter in determining the final rubber particle size if other processing conditions were held constant. In those cases where the graft modified PP was added to the PP matrix the steady-state torque was affected very little because of the lower levels of addition which were required to affect morphology. The torque ratio was varied mainly by varying the blending temperature.

Figure 5 shows the results of the dependence of rubber particle size on torque ratio. The particle size was the lowest at the minimum torque ratio of ~0.7 and increased with increasing torque ratio. The largest particle size obtained under the possible processing conditions was three times as high. These results are in agreement with both the Taylor droplet deformation theory[12,13] and the experimental results reported by Favis and Chalifoux[7], Avgeropoulos *et al.*[14], Danesi and Porter[15] and Wu[16].

Clearly in this range where torque ratios (and hence viscosity ratios) are increasing from 0.7 to 5.1 it is becoming progressively more difficult to disperse the rubber in a simple shear flow. Specific energy input during mixing also influences the rubber particle size and was combined together with the torque ratio into a single factor, P_p, as defined in equation (4). A useful linear relationship was found between this parameter and the rubber particle size over the range studied (*Figure 6*). It



Steady - state torques of blend components at different processing temperature.

Figure 4 Effect of processing temperature on steady-state torques

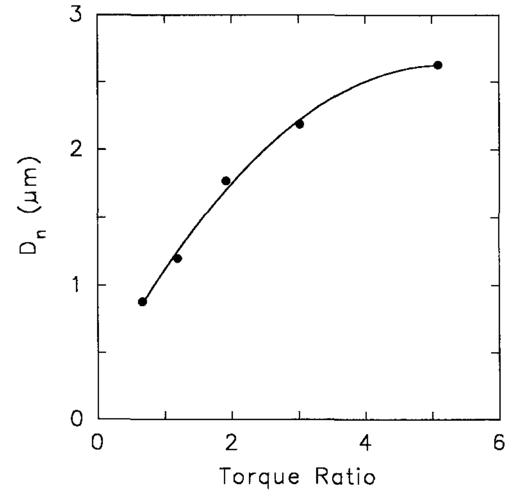


Figure 5 Influence of torque ratio on the D_n of non-reactive PP/NBR blends

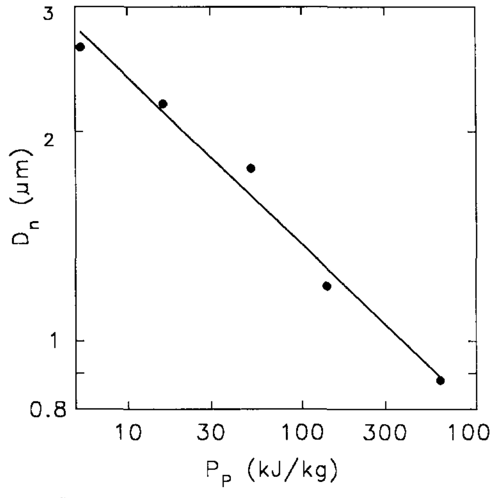


Figure 6 Influence of P_p on the D_n of non-reactive PP/NBR blends

is important to note that this linear relationship would not hold if the torque ratio could be continually lowered to a value that is much smaller than unity.

The other important factor in determining the final rubber particle size is the chemical reaction between the rubber and the matrix phase. The interfacial reaction was introduced by adding varying amounts of the oxazoline grafted PP into the matrix. *Figure 7* shows that the introduction of small amounts of reactive copolymer had a marked effect on the rubber particle size while retaining the same processing conditions. The rubber particle size decreased by a factor of three with the introduction of <0.025 wt% oxazoline functionality in the PP matrix when P_p was fixed at 50. A further increase of the oxazoline functionality did not greatly reduce the rubber particle size. The same trend of decreasing rubber particle size was also observed for other processing conditions though the reduction of rubber particle size was less remarkable at larger P_p (e.g. 140). This is, again, due to the fact that the rubber particles were smaller when the P_p was larger and smaller rubber domains are more resistant to further deformation. The above results are consistent with results reported by Willis and Favis[17].

The above results are significant in that they show the importance of both processing conditions and interfacial chemical reaction in determining the final rubber particle size and provide a method of controlling the rubber particle size using various combinations of processing conditions and amounts of interfacial reaction. In other words, various blends with the same number average rubber particle size may be prepared by using different combinations of P_p and the amount of interfacial chemical reaction. When the impact properties of these blends are compared with each other the role of interfacial reaction on toughening will be differentiated from the role of rubber particle size.

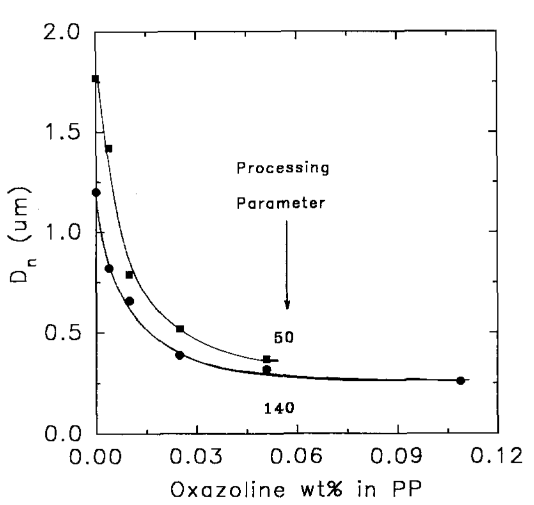


Figure 7 Influence of oxazoline concentration on the D_n of reactive PP/NBR blends (one processing condition for each curve)

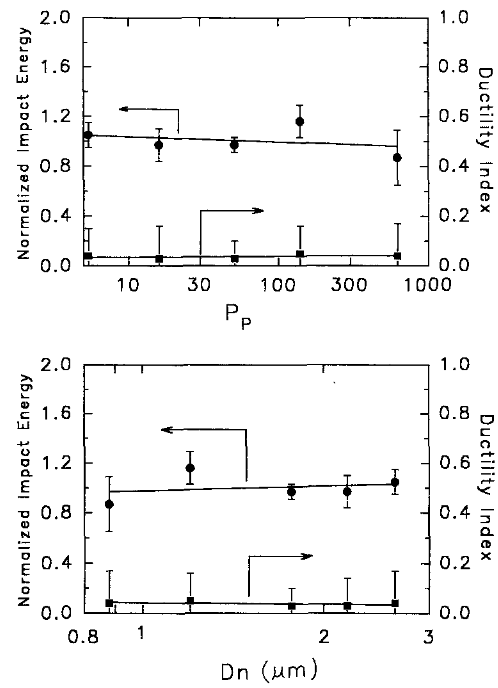


Figure 8 Influence of P_p and D_n on the normalized notched impact energy and ductility index of non-reactive PP/NBR blends

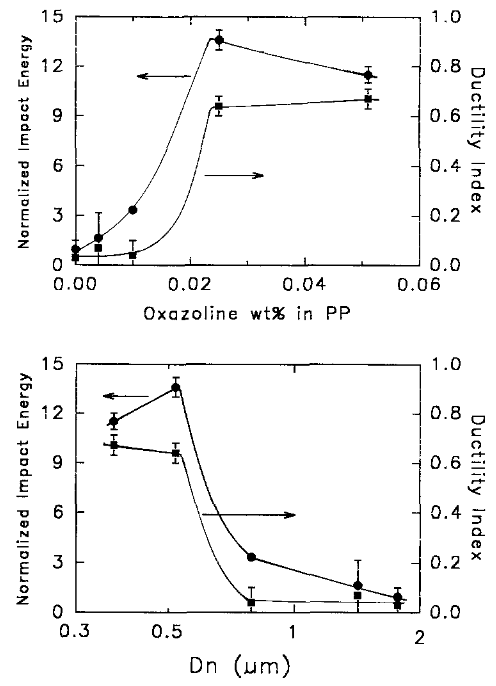


Figure 9 Effect of oxazoline concentration and D_n on the normalized impact energy and ductility index of reactive PP/NBR blends (notched) prepared at an identical processing condition ($P_p = 50$)

Effect of P_p *and interfacial reaction on notched impact properties*

The influence of P_p and rubber particle size on the normalized impact energy and ductility index of non-reactive PP/NBR blends is shown in *Figure 8*. Without any interfacial chemical reactions, the impact energies of the blends were about the same as that of pure PP, i.e. no toughening was achieved. Little or no stress whitening was observed. The ductility index was below 0.1 for all the non-reactive blends, indicating brittle failure. These results demonstrated that the addition of the NBR rubber to PP has little effect on the impact properties regardless of the particle sizes if there is no interfacial chemical bonding.

Figure 9 shows the effect of oxazoline concentration in the matrix and particle size on the normalized impact energy and ductility index while retaining the same processing conditions ($P_p = 50$). It is important to note that the presence of the interfacial chemical reaction permitted smaller average particle sizes than by adjusting with P_p alone. The blends went through a brittle–tough transition at ~0.02 wt% oxazoline functionality in the PP matrix and a particle size of ~0.6 μm.

Figure 10 shows the typical notched impact curves for PP and PP/NBR blends with various oxazoline concentrations in the PP matrix. The force dropped sharply to zero after the maximum load for both pure PP and the non-reactive blend and their total displacements were small, indicating brittle failure. The reactive blend with 0.010 wt% oxazoline concentration showed a significant increase in impact energy and total displacement but still experienced brittle failure. Upon the introduction of 0.025 wt% oxazoline functionality in the PP matrix, the impact failure became ductile, with a stable decrease of force after the maximum. The total displacement increased so drastically that the blend specimens did not break completely during the impact event (the top edges were not separated). Further increase in oxazoline concentration led to a slight decrease in both the maximum force and the impact energy. The ductility of the blend did not decrease. This dramatic improvement in impact energy and ductility suggests a significant change in failure mechanism.

Role of interfacial bonding independent of particle size

From *Figure 9*, it is very difficult to tell whether the impact improvement and the brittle–tough transition resulted from interfacial chemical bonding itself or they were simply a result of particle size reduction due to the introduction of the interfacial chemical reaction. In *Figure 11*, the normalized energies for both non-reactive and reactive blends are plotted against the rubber particle size. The curve for reactive blends was obtained at an identical P_p and varying amounts of interfacial reaction. With the same rubber particle size, the normalized impact energy for a reactive blend is clearly higher than that for a non-reactive blend. Therefore, interfacial chemical reaction not only greatly aids in reducing the rubber particle size but plays a further direct role in improving the impact properties of PP/NBR blends.

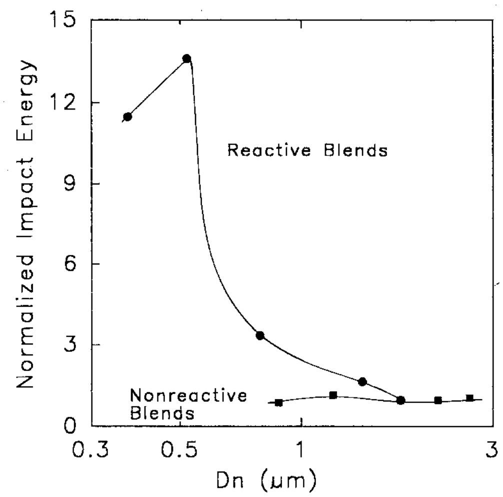


Figure 11 Effect of D_n and interfacial reaction on the normalized impact energy of notched PP/NBR blends

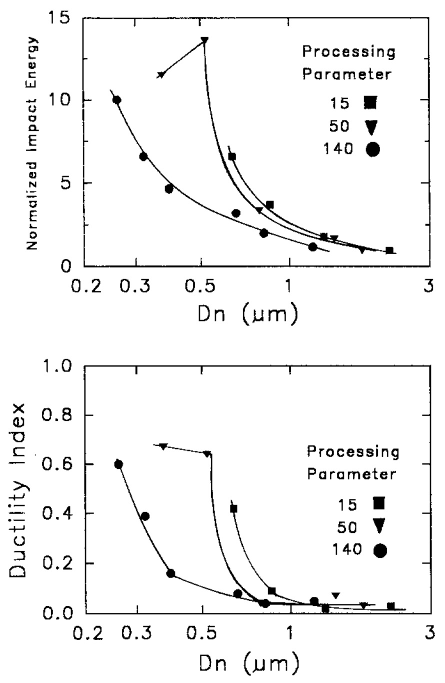


Figure 12 Role of interfacial reaction and D_n on the brittle–tough transitions of notched PP/NBR blends (each curve was obtained at an identical P_p but varying amounts of interfacial chemical bonding)

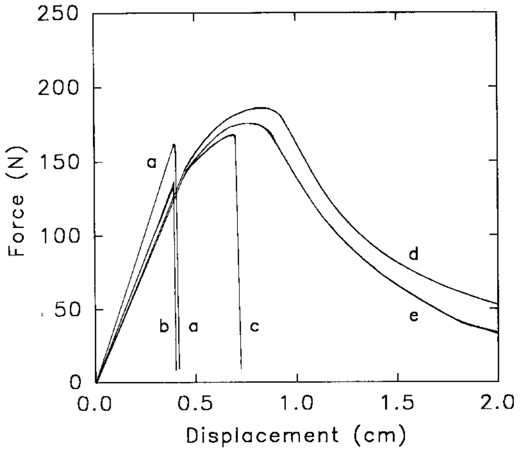


Figure 10 Notched impact curves for (a) PP, (b) non-reactive PP/NBR blends, and (c), (d) and (e) reactive blends with 0.010%, 0.025%, and 0.051% oxazoline concentration, respectively ($P_p = 50$)

The individual role of interfacial chemical bonding independent of rubber particle size can also be seen in *Figure 12*. The normalized impact energy and the ductility index of various PP/NBR blends are plotted against the particle size, where each curve was obtained by varying the amount of oxazoline functionality in the matrix while retaining an identical processing condition. The fact that brittle–tough transitions occurred only when the oxazoline functionality in the matrix phase reached relatively high levels indicates that interfacial chemical bonding is required for the brittle–tough transitions to occur. The brittle–tough transitions are sharper in the plot of ductility index than in that of normalized impact energy. This is probably because there was significant improvement in the impact energies of the blends below the transitions as a result of increased localized shear yielding.

Visual examination of the impacted samples showed that there was no significant stress-whitening in the non-reactive blends and only slight stress-whitening in the reactive blends below the brittle–tough transition. For reactive blends above the brittle–tough transition stress-whitening of the whole fractured surface was

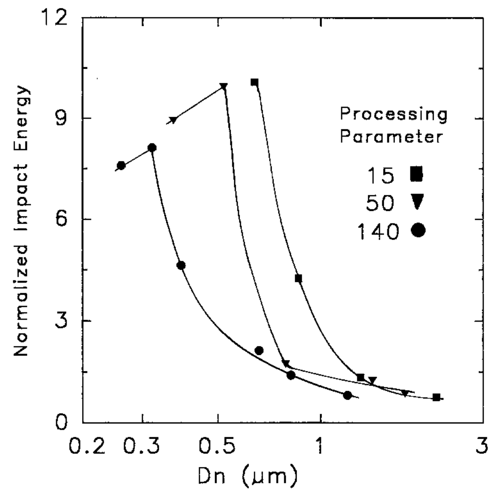


Figure 13 Role of interfacial reaction and D_n on the normalized impact energies of unnotched PP/NBR blends (each curve was obtained at an identical P_p but varying amounts of interfacial chemical bonding)

observed indicating significant dilation within the material. The considerable main chain flexibility and molecular entanglement of PP likely eliminates crazing as an explanation for the dilation. In addition the rapid change in mechanical response with increasing oxazoline concentration in the matrix signals increased interfacial bonding and probably eliminates interfacial debonding as the explanation for the dilation. It is believed that the dilation is a clear signal of cavitation within the rubber particles. The rubber particles, with their relatively low Young's modulus and low maximum stress, cavitate from within releasing hydrostatic tension. After the applied constraint is relieved by the cavitation, plastic flow may occur in the matrix, particularly in the relatively thin ligaments between the cavitated rubber particles[18–20]. This cavitation within the rubber followed by delocalized yielding can explain the large changes in impact strength observed.

The above analysis leads to conclusions in contrast to the suggestion by Wu[2] and Borggreve *et al.*[3,21] that interfacial chemical bonding is not necessary in toughening a pseudoductile polymer. It may be possible that in Borggreve's work the concentrations of maleic anhydride in the rubber used to toughen the PA were all above a threshold level above which further interfacial bonding has little effect.

Impact properties of unnotched disc specimens

Comparable studies were also performed on unnotched disc specimens of various non-reactive and reactive blends and the results were very similar. There was no improvement in impact energies of the non-reactive blends over pure PP whereas, for reactive blends, brittle–tough transitions similar to those in the notched samples were observed with impact energy improvement of up to ~10-fold. The individual role of interfacial chemical bonding on toughening is demonstrated in *Figure 13*. Each curve was obtained by varying the amount of oxazoline concentration in the PP matrix while retaining identical processing conditions. The shapes of the curves were similar to those for notched samples but the maximum improvement in impact energy was smaller and the transitions were sharper and occurred at slightly larger particle sizes. As in notched samples, no significant stress-whitening was observed for non-reactive blends and only slight stress-whitening in reactive blends below the brittle–tough transitions. Stress-whitening of the whole sample was observed for reactive blends above the brittle–tough transitions. The similarity between the test results for unnotched discs and notched Charpy bars is striking, not only because of different in-test geometry but also because of differences in skin–core morphologies that would be expected in filling moulds of different geometries. It would appear that the effect of the interfacial bonding overwhelms these two effects.

CONCLUSIONS

1. PP containing a basic functional group, oxazoline, has been successfully prepared by the melt grafting of 2-iso-propenyl-2-oxazoline onto a homopolymer PP.
2. The rubber particle size of PP/NBR blends can be effectively controlled by carefully varying either the processing conditions or the amount of interfacial reaction or a combination of both. Blends with the same rubber particle size can be obtained by using different combinations of processing conditions and the amount of interfacial reaction such that the role of interfacial chemical bonding on toughening can be differentiated from that of rubber particle size.
3. Without any interfacial chemical bonding, the impact energies of PP/NBR blends were about the same as pure PP. Interfacial chemical bonding is required for ductile failure to occur in toughened PP. The improvement in impact energies of PP/NBR blends above the brittle–tough transitions was up to 13.5-fold for notched samples.
4. The impact improvement is consistent with a mechanism which involves cavitation within the rubber particles followed by plastic flow in the ligaments of the matrix phase.
5. More generally, interfacial chemical bonding plays an important direct role in toughening pseudoductile polymers just as it does in brittle polymers.

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