

Rubber Toughening in Polypropylene: A Review

J. Z. LIANG,^{1,2} R. K. Y. LI¹

¹ Department of Physics and Materials Science, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong

² Department of Chemical Machinery, South China University of Technology, Guangzhou 510641, People's Republic of China

Received 23 April 1999; accepted 12 October 1999

ABSTRACT: The recent advances in the studies of the toughening methods and theories of polypropylene (PP)–elastomer blends are reviewed in the present article. Inclusions are key to toughening PP; they can play the role of agent-induced crazing, cause shear yielding of the matrix around them, and end the propagation of cracks. The major theories interpreting the toughening mechanisms of the blends are: multiple crazing, damage competition theory, shear-yielding theory, microvoids, and cavitation theories. The factors affecting the toughening effect are relatively complicated. Therefore, these theories have been verified only in some cases when they have been applied in relevant conditions. To achieve the objective of better toughening, it is important to improve the uniform distribution of dispersed-phase particle size and suitable filler size, as well as improving the dispersion of the inclusions formed in the matrix; in addition the matrix materials or fillers must be functional with suitable modifier in order to enhance the interfacial adhesion or to improve the interfacial morphological structure between the filler and matrix. However, the exact toughening mechanisms for PP–rubber blends have to be studied further because of complications resulting from the crystallinity of the matrix. © 2000 John Wiley & Sons, Inc. *J Appl Polym Sci* 77: 409–417, 2000

Key words: polypropylene; toughening; elastomer particulate; blend

INTRODUCTION

Polypropylene (PP) is a thermoplastic widely used in packaging and in the textile and automobile industries because of its good processibility. However, its application as an engineering thermoplastic is somewhat limited because of its relatively poor impact resistance, especially at room and low temperatures. To improve its impact toughness and extend its application range, a number of extensive and thorough studies on toughening PP with particles have been made in

the last 20 years. Filling compounding or blending is an effective, simple, and economic way for modifying polymers and developing new functional polymeric materials. The methods of toughening and reinforcing PP are divided into four main types: rigid organic particle (ROP)–filled PP, rigid inorganic particle (RIP)–filled PP, blending PP with rubber, and ROP- or RIP-filled PP–rubber blends. There are more differences in the toughening and reinforcing mechanisms for these composites. Among them, increasing attention is being paid to RIP- and ROP-filled brittle polymers, referred to as nonelastic toughening. Generally speaking, the toughening effect for PP–rubber blends is much better than that for PP–ROP composites and PP–RIP composites, but the stiffness and strength of the former will obviously be decreased. For brittle or quasi-brittle matrix

Correspondence to: J. Z. Liang, Department of Chemical Machinery, South China University of Technology, Guangzhou 510641, P.R. China.

Journal of Applied Polymer Science, Vol. 77, 409–417 (2000)
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materials, there are different toughening and reinforcing effects and mechanisms under various processing or testing conditions. It is quite necessary, therefore, to understand the toughening and reinforcing mechanisms of particulate-filled PP in order to design and develop an advanced PP with good performance and processibility.

In this article the authors review studies from the last 20 years about advances in mechanisms for toughening PP–elastomer blends.

BACKGROUND

Because rubber has excellent elasticity and toughness, great attention has been paid to PP modified with rubber materials since the 1970s.^{1–29} These studies of toughening mechanisms for PP–rubber blends are generally divided into four areas: (1) study of the structure–impact property relationship; (2) the toughening effects of the content, shape, size, and distribution of rubber fillers and the dispersion of the particles in the matrix; (3) the influence of interfacial adhesion and compatibility between the matrix and fillers; and (4) the effects of processing and testing conditions on toughening.

Structure–Impact Property Relationship

Material properties mainly depend on their micromorphological structure under given measuring conditions, especially the interfacial morphological structure between the matrix and fillers for polymer blends and their composites. As a result, the structure–property relationship has been investigated to interpret the toughening mechanism of PP–rubber blends.^{2,4,6,15,18} The morphology of PP–rubber blends is closely related to the compatibility between the continued phase and the dispersed phase.² In addition, the effect of processing and shaping conditions on morphology is significant for crystalline polymers. For example, different morphological structures were found at skin and core layers of a molded tensile bar due to crystalline and molecular chain orientation of the PP matrix during injection.⁴ More recently, Van der Wal et al.²⁹ investigated the effects of matrix properties on impact behavior of a PP/ethylene-propylene-diene monomer copolymer (EPDM) blend, pointing out that the impact strength was determined as a function of temperature and that the matrix crystallinity was varied by varying the matrix isotacticity. In 1990 Wu¹⁵

demonstrated a direct relationship among chain structure, phase morphology, and toughness in polymer–rubber blends: the dispersed rubber toughens a polymer–rubber blend mainly by promoting energy dissipation of the matrix, and the toughening efficiency correlates with the rubber phase morphology and the chain structure of the matrix.

Effects of Particle Shape, Content, Size, and Size Distribution

The shape, content, size, and size distribution of the dispersed-phase particles are important factors affecting the toughening effect of PP–rubber blends, which are related to the micromorphological structure of the materials. Jang et al.⁷ used transmission electron microscopy (TEM) and computer-aided image analysis to provide rubber particle size information and observed the effects of the rubber particle size on the crazing in the PP matrix. The results showed that PP blends with smaller rubber particles are tougher and more ductile than those with larger particles. This is probably because the former represents a more efficient action of the rubbery phase in inducing crazing and/or shear yielding of the matrix for small rubber particles. Phadke and De⁸ studied the effect of cryoground rubber (CGR) on the melt flow and mechanical properties of PP. The results indicated that PP blended with CGR in powder form showed poor adhesion to the PP matrix and, therefore, decreased the impact strength at higher loading, while the addition of a master batch of CGR and natural rubber (NR) improved the impact strength of PP. This is because NR was found essential as a dispersing agent, leading to the uniform dispersion of the CGR particles in the PP matrix. Pukanszky et al.¹⁶ also observed the effect of rubber particle size on some mechanical properties of PP–EPDM. Under the same test conditions, the elongation at break values of PP–EPDM blends decrease with an increasing number average of the particle size. On the other hand, the larger the rubber particle size, it's expected that the easier it will be for the cavitation to take place.³⁰ Therefore, there is the best particle size for the toughening effect. In addition, particle breakup, coalescence, and eventual degradation of the matrix also influence the actual particle size. Liu et al.²⁵ pointed out that the influence of the rubber particle size distribution on the brittle–ductile transition behavior of PP–rubber blends is an important factor.

As stated above, the impact toughness of polymer–rubber blends increases obviously with the concentration of elastomer. More recently, Van der Wal et al.³¹ studied the effect of rubber content on the deformation and impact behavior of PP–EPDM blends and found that PP can effectively be toughened by blending with EPDM.

Influence of Interfacial Adhesion and Compatibility

Interfacial adhesion between the matrix and fillers affects not only tensile strength but also the impact strength of composite materials. The results of Phadke and De³ indicated that cryo-ground rubber (CGR) in the powder form showed poor adhesion to PP matrix because PP was thermodynamically incompatible with natural rubber and CGR. Therefore, impact strength decreases at higher loading. With the addition of natural rubber and CGR in the form of a master batch, the adhesion of CGR to the PP matrix was improved, and the impact strength was increased as a result. Compatibility between two polymer phases affects not only the interfacial adhesion but also the size and distribution of the dispersed phase, as well as the uniformity of the dispersed phase in the continual phase. As a result, the strength and toughness of the blend are directly influenced. When rubber (SEBS) was grafted with a suitable content of maleic anhydride (MA), the rubber particles were dispersed uniformly in the continuous nylon matrix and the PP was encapsulated by thin layers of the rubber (i.e., the shell–core structure), thus the tensile strength and ductility of the blends were enhanced obviously.²⁶ Recently the authors got similar results²⁷ from an investigation of the effects of rubber (EPDM) made functional with MA on the impact toughness of PP blends.

In general, besides the properties of the matrix, the toughening mechanisms of polymer–rubber blends had a relationship to the interfacial adhesion between the filler and matrix. For a blend system with strong interfacial adhesion, multiple crazing is favored; for a blend system with poor interfacial adhesion, shear yielding is favored. In addition, toughening mechanisms are related to the matrix property.

Effects of Processing and Testing Conditions

As mentioned above, PP is a crystalline thermoplastic resin, and its micromorphological structure, such as crystallinity, crystalline size, and

orientation degree, very much depends on processing conditions (temperature and temperature gradient, flow rate, pressure, etc.). As a result, the influence of processing conditions on the mechanical behavior of polymeric composites or blends will be significant. For example, the mechanical properties of the skin and the core layers of molded PP or PP alloy tensile bars or sheets are very different. When PP is modified with rubber particles, the factors affecting its micromorphological structure are more complex.

Apart from processing conditions, the effects of testing conditions on the mechanical behavior of particulate-filled PP composites or blends are also significant. PP shows a clear brittle–ductile transition (BDT) with a rise in temperature under notched impact conditions.²⁸ This BDT temperature shifts to a higher temperature with increasing crystallinity of PP.²⁹ Jang et al.⁵ pointed out that plastic deformation mechanisms of PP–rubber blends depend on the test rate and temperature, with high rates and low temperatures favoring crazing and high temperatures and low strain rates favoring shear yielding.³ The rubber particles, in addition to promoting crazing and shear yielding, can also improve the fracture resistance of PP by varying the crystalline structure of PP (e.g., reducing the spherulite dimension.⁵) The results of rubber-modified PP in experiments conducted by Chou et al.¹⁰ show that the size and density of the damage zones increase in a gradual manner through the ductile–brittle transition whether examined as a function of temperature, strain rate, or blend composition. Similarly, the deformation behavior of blends of PP modified with rubber was found as a function of temperature and composition under tension.

TOUGHENING THEORY

Since Merz et al.³³ proposed the microcrack theory in 1956, there have been a number of toughening theories for polymer–rubber blends, such as the shear-yielding theory, multiple-crazing theory, and shear band/crazing interaction theory. However, most toughening theories proposed before 1980s were based on an amorphous polymer modified with rubber. In fact, either brittle or ductile polymers can be divided into amorphous and crystalline polymers. For the latter, the toughening mechanisms are more complicated, which is why there have been relatively few

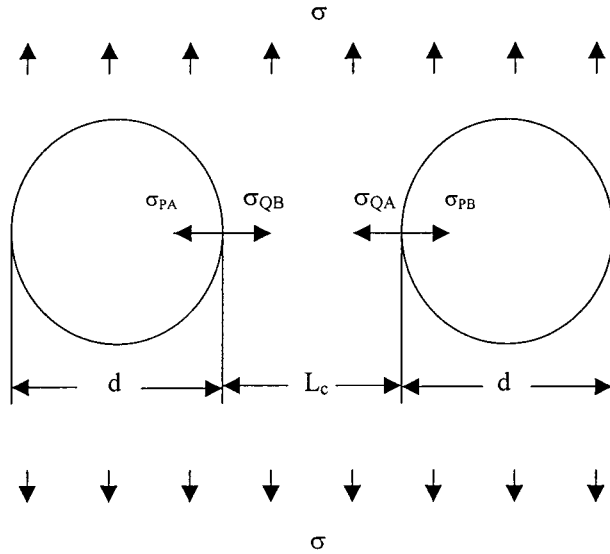


Figure 1 Diagram of stress interaction between adjacent particles.

toughening theories for systems of crystalline polymer modified with rubber.

In the last 10 years some important advances in this field have been made, and some new toughening theories and brittle–ductile criteria have been presented, with critical ligament thickness, critical plastic area, voiding and cavitation, and damage competition constituting the majority of these theories.

BDT Criterion and Percolation Model

In 1985 Wu^{6,13} studied the relationship between the impact strength and rubber content of Nylon-6–EPDM blends and got a BDT master curve and proposed a concept of the matrix ligament thickness, L , defined as the nearest distance of the matrix between two neighboring rubber particles, as shown in Figure 1. When the average ligament thickness is smaller than the critical ligament thickness, L_c , the blend will be tough; when greater, it will be brittle. In other words, the BDT will occur at L_c . The L_c is independent of particle volume fraction and particle size and is characteristic of the matrix alone for a given mode, temperature, and rate of deformation. For blends with dispersed spherical particles, L_c is given by¹³

$$L_c = d_c [k(\pi/6V_f)^{1/3} - 1] \quad (1)$$

where d_c is the critical particle diameter, V_f the particle volume fraction, and k the geometric constant. For example, $k = 1$ for cubic lattice.

When the average ligament thickness is smaller than the critical value, a blend will be tough; when greater, it will be brittle.^{6,13} This is because if L is smaller than L_c , a plane–strain to plane–stress transition would occur; the ligament would shear-yeild, and the blend would be tough. On the other hand, if L is greater than L_c , such transition would not occur, and the matrix ligament would fail in a brittle fashion.

From the viewpoint of percolation theory, Margolina and Wu¹² proposed a concept of stress volume sphere (Fig. 2): the BDT of a PP–rubber blend system can be described by a percolation process of a stress volume sphere; when $L < L_c$, two neighboring spheres overlap, and at the percolation threshold the spheres contact, causing the onset of a BDT. In this case, the critical diameter of the stress sphere is expressed as

$$S_c = d_c + L_c \quad (2)$$

When the volume fraction of the stress volume sphere, V_s , reaches the critical value, V_{sc} , the spheres yield, and the continuum percolation will occur, which corresponds to the BDT. Since $V_f \sim d^3$, and $V_s \sim S^3$, the critical condition of BDT can be written as

$$V_{sc} = V_{fc}(S_c/d_c)^3 \quad (3)$$

According to the scaling law of percolation, a relationship among the toughness of materials G , V_s and V_{sc} can be expressed as

$$G \sim (V_s - V_{sc})^g \quad (4)$$

where g is the critical exponent, which is about 0.45.

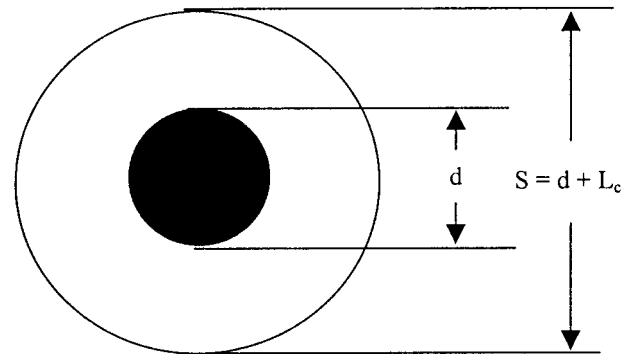


Figure 2 Schematic of stress volume around a rubber particle. The rubber particle is shaded.

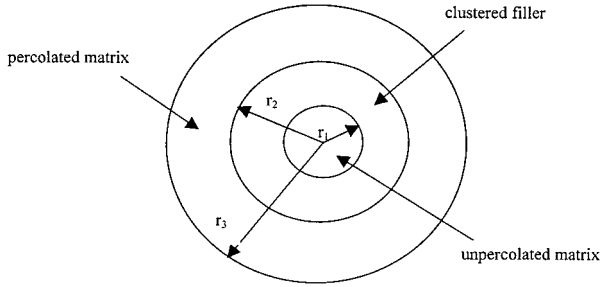


Figure 3 Diagram of a model of stress sphere volume.

In polymer blending or specimen-injection molding, it's easy for the aggregation of the filler in the matrix to take place. In this case, the matrix encircled by the filler may be unpercolated when the other matrix is percolated (Fig. 3). Considering the aggregation phenomenon of inclusions in the matrix in practical blending and the basis of the concept of stress sphere, the authors³² proposed a modified equation describing the relationship between the stress volume fraction (V_s) and V_f :

$$V_s = V_f \left[\frac{\pi}{6V_{fc}} + V_f - \frac{6V_{fc}}{\pi} \right] \quad (5)$$

where V_{fc} is the critical volume fraction of the particles.

Damage Competition Theory

It is known that the mechanisms causing damage during the brittle–ductile transition for thermoplastics are mainly crazing, microcracks, and cavitation in the brittle region and shear yielding in the tough region. When the yield deformation process is dominated by shear flow, the material will have tough damage; if the process is dominated by crazing and the crazing is not blocked by rubber particles, then the material will have brittle damage. That is, the appearance of shear yielding is the brittle–ductile transition point. Therefore, the brittle–ductile transition is the result of competition between the brittle-fracture mechanism and shear-yielding mechanism. From this, the damage competition dimensionless number, a criterion of the brittle–ductile transition, is defined as

$$N_d = \sigma_{bc}^2 / \sigma_{yc}^2 \quad (6)$$

By comparing this equation with the Ludwik–Davidenkov–Orowan theory,³⁴ the brittle–ductile transition damage competition criterion can be defined: when N_d is smaller than 1, the polymer blend will fail in a brittle fashion; if N_d is greater than 1, the blend will be tough; and as N_d is equal to 1, the brittle–ductile transition will occur.

Recently, based on the Ludwik–Davidenkov–Orowan theory, Lyu et al.³⁵ proposed a new criterion of BDT for polymer–rubber blends as follows:

$$N_d = F_g L_{ym} / L_D \quad (7)$$

and

$$L_{ym} = G_{cm} E_m / \sigma_{ym}^2 \quad (8)$$

$$F_g = 4\delta / \pi \quad (9)$$

$$L_D = d \frac{(1 + 1.27V_f^{2/3})(1 - 1.21V_f^{2/3})^2}{1 + \alpha V_f} \quad (10)$$

where δ is a factor related to the plane–stress state and α the constant related to the interfacial adhesion. The subscript m stands for the matrix.

Shear-Yielding Theory

Under the action of outside force, dispersed-phase particles will play the role of stress-concentration bodies to cause three-dimension stress concentration, and to induce the volume-expanding processes of cavitation, interfacial debonding, matrix crazing, and so forth. Thus the matrix around the particles will produce shear yielding. With decreasing distance between neighboring particles, the stress field caused by neighboring particles will be overlapped and the shear-yielding region will be expanded further. In this case, the blend will appear to have macrotoughness damage and the BDT will occur. On the other hand, the crazing will be effectively controlled by rubber particles to avoid developing as cracks when the interfacial adhesion between the matrix and the particles is good. In this case, the brittle–ductile transition will appear and the toughness of the PP–rubber blends will be remarkably improved.

Chou et al.¹⁰ observed the damage in a irreversible deformation region for PP and EPR modified PP using optical microscopy (OM) and scanning electron microscopy (SEM) and found that at -40°C , the controlling and irreversible deforma-

tion process in PP was crazing; in the blends two kinds of damage zones were observed: a diffuse zone due to voiding at rubber particles and an intense damage zone due to crazelike damage and deformation bands.

Sjoerdsma¹⁴ believes that the stress-concentration region of the particles can be described using an equivalent circle and that the only overlapping stress-concentration field of the matrix between two neighboring particles will occur as shear yield; these shear-yielding fields will join each other with decreasing L ; when $L = L_c$, the blend appears as tough damage and the BDT occurs. The ratio of the square of V_f to the particle diameter was constant (A) in this case. Thus, a new criterion of the BDT is expressed as

$$V_f^2/d_c = A \quad (11)$$

Cavitation Theory

The stress analysis results show that the stress at the equatorial plane of dispersed-phase particles is maximum due to stress concentration under the action of an outside force. Therefore, interfacial debonding between the matrix and fillers will occur first at this place, forming microvoids. In addition, because of the difference in Young's modulus and Poisson's ratio between the dispersed-phase rubber particles and the plastics matrix, the cavitation phenomenon will take place in a rubber particle when breaking stress is reached, and there is no tendency for debonding at the interface if the interfacial adhesion is stronger.³⁶ These microvoids, or cavities, also absorb deformation or fracture energy to produce the BDT in addition to shear yielding of crazing of the matrix. This is the concept of microvoid toughening in polymers, which has been studied both theoretically^{33,34} and experimentally.^{38,39} Previously, the microvoids were usually created by means of nonadhering particles; Bagheri and Pearson⁴⁰ used hollow plastic microspheres to generate holes for toughening an epoxy resin. The results showed that the use of hollow plastic microspheres provided greater yield strength than that of similar blends with equivalent rubber content. Lazzeri and Bucknall²⁰ pointed out that deformation begins with cavitation of the rubber particles and progresses through the growth of dilatational bands, which are cavitated planar yield zones combining in-plane shear with extension normal to the band.

The production of cavitation is intimately related to the properties of the matrix materials. In general, for dispersed-phase particles with a higher Poisson's ratio value and a lower breaking stress, such as rubber, it should be beneficial for a lower cavitation strain of polymer blends. This may be a reason the toughening effect of rubber-modified PP blend is higher than that of rigid particulate-filled PP composites.

Estimation of Energy Absorption Assignment

In 1983 Wu⁴¹ studied impact mechanisms in a nylon 66-rubber system and noted that the impact energy should be contributed by the surface energy (G_s), the crazing energy (G_z), and the matrix-yielding energy (G_y). That is

$$G = G_s + G_z + G_f \quad (12)$$

The results showed that G_z was about 25% of G , while G_y was about 75% of G . This suggests that the key to the toughening effect is how to make the matrix yield for a ductile polymer modified with a rubber system.

Relationship Between Structure and Toughness

The objective of studying toughening mechanisms is to reveal the structure-property relationship of materials. Discussion about the theories already mentioned is limited to giving only qualitative explanations and conjectures about the experimental results, while there are relatively few quantitative investigations on the morphological structure of materials at molecular level and on the morphological structure-material toughness relationship. Recently, Wu¹⁵ introduced two molecular structure parameters from high molecular chain structure characterization—chain entanglement density (v_e) and the characteristic ratio of the chain (C_∞)—and proved there was a correction between the matrix craze-inducing stress (σ_z) and the critical yielding stress $\{\sigma_y\}$ as follows:

$$\sigma_z \propto v_e^{1/2} \quad (13)$$

$$\{\sigma_y\} \propto C_\infty \quad (14)$$

From a discussion of the relationship among σ_z , $\{\sigma_y\}$, v_e , and C_∞ , Wu proposed a criterion for crazing-shear-yielding competition: when $\sigma_z < \{\sigma_y\}$, the matrix tends toward crazing; in the

opposite situation, it tends toward shear-yielding damage.

Scientific Classification of Thermoplastics Matrix

It is generally believed that there are different toughening mechanisms for various types of thermoplastic polymer matrixes. On the basis of the previous experimental results of both themselves and other researchers, Wu⁶ divided thermoplastic polymer matrixes into two types, brittle matrix and ductile matrix, and noted the characteristics of energy absorption when each matrix is damaged. For rubber-toughening brittle polymer systems, such as PS and PMMA, the external impact energy is mainly dissipated by the formation of crazing in the matrix. On the contrary, for rubber-toughening ductile polymer, the dissipation of the external impact energy depends on the shear yielding of the matrix.

DISCUSSION

Main Factors Affecting Toughening and Reinforcing

For given particles the stress is borne mainly by the matrix if the concentration of the particles is too low. That is, the toughening effect is insignificant because L is much higher than L_c . But when the concentration increases to some extent, the toughening effect decreases. This is because the interaction among particles cannot be neglected as the adjacent particles are closer to each other. As shown in Figure 1, when L is sufficiently large, particles A and B are subjected to compressive stresses σ_{PA} and σ_{PB} , respectively, under the action of a uniform outside stress field; but particles A and B will be closer to each other with increasing V_f . In fact, in this case their compressive stresses should be $\sigma_{PA} - \sigma_{QB}$ and $\sigma_{PB} - \sigma_{QA}$, respectively, reflecting both the decrease in compressive stress undergone by the matrix around the particles and had brittle-ductile transition. Thus, for given particles (the size is constant), the matrix ligament achieves a critical concentration, L_c , at which the toughening effect is best. This may explain why the phenomenon of maximum fracture toughness occurs at some concentration of the particles.

When the diameter of particles is smaller, the required concentration that achieves the same interfacial ligament thickness should be lower. In general, PP blends with smaller rubber particles

are tougher and more ductile than those with larger particles, probably because the former represent a more efficient use of the rubbery phase in promoting crazing and/or shear yielding.⁷ But this is not to say that the smaller the particle, the better the toughening effect. This is because the propagation of the crack depends on the fracture ligament at the end of the crack. If the dimension of the particle in the matrix is smaller than the size of the fracture ligament, then the existence of the particle around the front of the crack only changes the rheological properties of the matrix and cannot influence the propagation of the crack; on the contrary, if the size of the particle is big enough to block the propagation of the crack, then the toughness of the composite will be improved. The experimental results show that when the average diameter of rubber particles, $d_{av} \geq 0.5 \mu\text{m}$, the PP blends exhibit pronounced crazing.⁷

Wu¹⁵ investigated the influence of chain structure and phase morphology on the toughness of polymer-rubber blends, noting that at the same amount of rubber, the extent to which a matrix could be rubber-toughened depended on the intrinsic brittleness-ductility of the matrix polymer; the optimum rubber-phase morphology for toughening correlates with chain parameters such as entanglement density, ν_e , and characteristic ratio, C_∞ . It was found that a polymer glass tends to craze (brittle behavior), when $\nu_e \leq \sim 0.15$ mol/cc and $C_\infty \geq 7.5$; and it tends to yield (ductile behavior), when $\nu_e \geq \sim 0.15$ mol/cc and $C_\infty \leq 7.5$.

On the other hand, the addition of rubber inclusions such as EPDM will influence the crystallization and crystalline structure of PP, but the effect of the difference in crystalline structure on the mechanical properties of the blends is insignificant.⁴² Jang⁷ also pointed out that the highly oriented skin layer of an injection-molded tensile bar after deformation was free from crazing in contrast to the heavy crazing density in the randomly oriented spherulitic core zone.

In addition to particle size and particle content, the influence of morphological structure parameters such as the size distribution of fillers on the BDT of polymer blends or polymer composites should not be neglected. This is because particle size distribution affects the stress distribution in materials. Wu¹³ believed the matrix ligament thickness should be a function of the size, size distribution (σ), and content (V_f) of a rubber particle and proposed a relevant expression:

$$L(d, \sigma, V_f) = d[(\pi/6V_f)^{1/3} - 1]\exp(\ln^2 \sigma) \quad (15)$$

Recently, Liu et al.²⁵ presented a new equation that is generally applicable to binary polymer blends with a log-normal distribution of particle size and the configuration of well-dispersed particles in matrix as follows:

$$L(d, \sigma, V_f) = d[(\pi/6V_f)^{1/3} \exp(1.5 \ln^2 \sigma) - \exp(0.5 \ln^2 \sigma)] \quad (16)$$

They observed the BDT phenomenon of poly(vinyl chloride)/nitrile rubber, PP-EPDM, and PP/ethylene-vinyl acetate copolymer (EVA) blends, and found good agreement between the theoretical predictions and the experimental results.

How to Improve Toughness and Strength

Wu and Dong⁴³ made three-dimensional finite element analysis of composites with coated spherical inclusions to determine the internal stress. Their calculations show that stress distribution in the matrix and the mechanical properties is sensitive to the interface property in the three-phase composites; the change in aspect ratios of the interface and inclusions can also affect the internal stress concentrations and mechanical properties of the material. With increasing interfacial layer thickness, the values of σ_e decrease, and the distribution of σ_e around the particle obviously varies with decreasing Young's modulus of the interfacial layer.

Generally, the way to improve toughness and strength of filled polymers is to enhance the interfacial adhesion or to form a soft interfacial layer around the particle. Therefore, in ternary polymer composites such as PP-rubber-RIP, it is more efficient to produce a core-shell structure for toughening and reinforcing.

It is worth pointing out that PP made functional with modifier also can enhance the interfacial bonding between the continuous and dispersed phases, improve the uniformity of the dispersed phase in the continuous phase, form the fillers to a suitable size, or form an optimal morphological structure, such as the core-shell structure. Thus, the toughness of the PP blends can also be improved. For example, peroxide-treated PP-EPDM blends exhibited a considerably low BDT temperature, small particle size, and good ductility.²⁹ Generally speaking, rubber cavitation and matrix shear yielding are two coupled toughening mechanisms; which one occurs first depends on the properties of the matrix and the

rubber particles. Chen and Mai⁴⁴ also noted that rubber cavitation plays an important role in the toughening process under high tensile triaxial stresses.

CONCLUSIONS

Improving the impact toughness and stiffness of PP has important practical meaning for extending its range of applications. For particulate-filled PP composites or blends, the ability of inclusions to play a role in agent-induced crazing, shear yielding of the matrix and ended crack propagation is the key to toughening brittle or quasi-brittle polymeric materials. Obviously the impact toughness of PP can be enhanced by materials modified with rubber. Attention was paid early and extensively to this, even though the stiffness of the blends decreases with increasing filler content. Because of the addition of rubber into PP, variation of molecular structure can be induced, such as molecular weight and crystallinity, in addition to the compatibility and miscibility between the matrix and filler. Therefore, the factors affecting toughening effect of PP-rubber blends are more complicated than those of rigid inorganic particle-filled PP composites.

The major theories interpreting the toughening mechanisms of PP-rubber blends are: the multiple-crazing, damage competition, and shear-yielding theories and the microvoid and cavitation mechanisms. These theories have been verified only in applied relevant conditions or in some cases from more complicated factors affecting the toughening effect of the blends. Generally, rubber cavitation and matrix shear yielding are two coupled toughening mechanisms; which one occurs first depends on the properties of the matrix and rubber particles. To achieve the objective of a good toughening effect, it is necessary to improve both the uniformity of rubber particles in the PP matrix and the interfacial adhesion and morphological structure between the matrix and filler, as well as forming suitable particle size and distribution.

One author (J.Z.L.) was the recipient of a research studentship from the City University of Hong Kong during the course of this work.

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