

Effect of Compatibilization on the Properties of Polypropylene/Polyamide-66 (75/25 Wt/Wt) Blends

J. DUVALL,¹ C. SELLITTI,¹ C. MYERS,² A. HILTNER,^{1,*} and E. BAER¹

¹Department of Macromolecular Science and Center for Applied Polymer Research, Case Western Reserve University, Cleveland, Ohio 44106; ²Amoco Chemical Company, Research and Development, Naperville, Illinois 60566

SYNOPSIS

Interfacially compatibilized immiscible blends with an isotactic polypropylene matrix (PP) and dispersed polyamide-66 (PA) were prepared by extrusion with anhydride-grafted isotactic PP compatibilizers, one of high-anhydride content (HAC, 2.7 wt % grafted maleic anhydride) and one of low-anhydride content (LAC, 0.2 wt % anhydride). On a weight basis, HAC was more efficient than LAC in dispersing PA to submicron domains, but on a total weight % anhydride basis, both compatibilizers were equally efficient. Both compatibilizers imparted similar tensile strength improvement compared to an uncompatibilized blend. Maximum fracture strain was obtained at similar total anhydride content, but much higher maximum fracture strain was achieved with LAC than with HAC. Good adhesion in an 11.25 wt % LAC blend was seen at the microscale as fibrillar ligaments connecting PA particles to the drawn PP matrix. Interfacial failure was observed in a lower fracture strain composition, 11.25 wt % HAC. © 1994 John Wiley & Sons, Inc.

INTRODUCTION

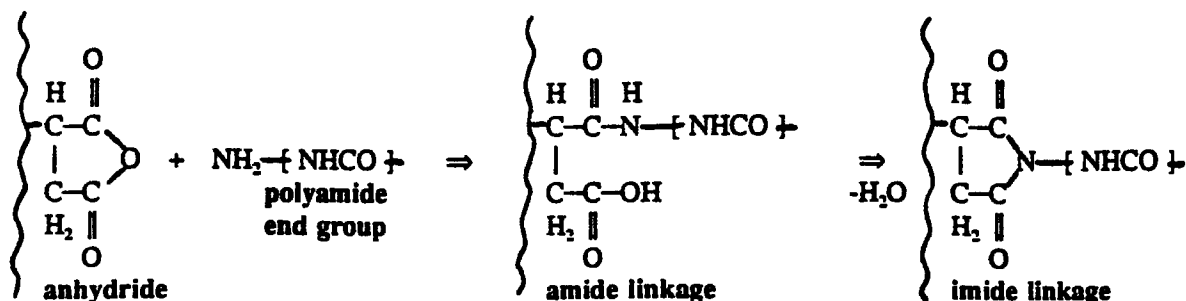
Multicomponent materials are frequently made by blending two or more miscible or immiscible polymers. The mechanical blending of miscible polymers results in a homogeneous morphology that exhibits a single glass transition.^{1,2} However, the mechanical blending of immiscible but compatible components, such as polycarbonate with acrylonitrile-butadiene-styrene, gives a multiphase morphology with efficient dispersion of the minor component and good interfacial adhesion between the two unmodified components.^{3,4} When incompatible thermoplastic polymers such as polypropylene (PP) and polyamide-66 (PA) are mixed, the interfacial adhesion is weak, which results in inferior mechanical properties and poor dispersion of the components. These blends require a compatibilizing agent to achieve satisfactory interfacial adhesion and interfacial stress transfer between the phases. One approach to polymer blend compatibilization is to manipulate

the interactions at the interface by the addition of "interfacial agents" that facilitate graft reactions.^{5,6}

PP is often blended with other polymers to improve its performance in specific applications. The addition of a PA serves to significantly increase the yield strength of the material if the components can be made to interact constructively. Functionalized PP compatibilizers are popular third components that are added to aid both adhesion and mixing in the PP/PA system. Compatibilizing agents for these blends have been developed by grafting maleic anhydride onto polypropylene chains where the amount of grafted anhydride can be varied.^{7,8} In PP/PA blends, the PP-grafted-maleic anhydride (PP-g-MA) compatibilizer forms a chemical linkage through the reaction of anhydride groups with the polyamide end groups. Consequently, a graft copolymer with segments of PP and PA is formed *in situ* at the interface. The graft copolymer improves interfacial compatibility by association of the different segments with their respective components. Since the compatibilizing process occurs by reactive mixing, special consideration must be given to the amount of maleic anhydride graft used in the compatibilizing agent.

* To whom correspondence should be addressed.

Previous studies have shown PP-*g*-MA to be an effective compatibilizer for PP/PA6 blends.⁹⁻¹² Compatibilization is considered to occur through chemical linkage of the anhydride on the compatibilizer chain and the PA end groups. This is similar to the reaction previously proposed by Ide and Hasegawa⁹:



where polyamide end groups at the interface are chemically reacted with anhydride groups on the compatibilizer during melt mixing. Model reactions of amines with anhydride-grafted polypropylene at melt temperatures proceed to imide linkages, but it is difficult to determine the amide vs. imide structure in the PP/PA blends. The formation of the graft copolymer through the reaction of the anhydride with the polyamide end group has been confirmed through solvent extraction.^{9,10} The grafted copolymers preferentially reside at the interface and improve interfacial adhesion through the chemical linkage across the interface.

Formation of the graft copolymer during reactive mixing significantly changed the rheological properties of the blend. The unmodified PP/PA6 blend produced a negative deviation from the same curve, which indicated incompatibility of the blend components. A positive deviation from the viscosity-composition curve predicted by the rule of mixtures in compatibilized blends indicated strong interactions between the blend components. A TEM study revealed that a 260 Å-thick layer of graft copolymer formed at the phase boundary during melt mixing of the compatibilizing agent with PA6.¹⁰

PP-*g*-MA compatibilizers have been shown to improve the dispersion, interfacial adhesion, and mechanical properties in PP/polyamide-6 (PP/PA6) blends.⁹⁻¹² The compatibilizer efficiently dispersed the polyamide as the average particle size decreased from 10 to less than 1 μm. The addition of PP-*g*-MA compatibilizer also increased the fracture strain from 6 to 30% in a 80/20 PP/PA6 blend, indicating that the interfacial adhesion was also improved.

Other modified PPs such as acrylic acid-functionalized PP¹³ that have been used to compatibilize PP/PA6 blends also improved the properties. The application of grafted polyolefin compatibilizers extends to other polyolefin blends. Polyethylene/PA6 blends have been compatibilized by the addition of PP-*g*-MA or functionalized polyethylenes,¹⁴ whereas

anhydride-functionalized polystyrenes have reactively compatibilized blends of PA6 with polystyrene.¹⁵

The present study was aimed at understanding the relationship between the nature of the compatibilizer and the resulting blend morphology and properties. In particular, PP-rich PP/PA blends were investigated using two compatibilizers with widely different graft anhydride concentrations.

EXPERIMENTAL

Materials

Blends of polypropylene (PP) and polyamide-66 (PA) were supplied by the Amoco Chemical Co. The polyamide was DuPont Zytel 101; titration of the end groups gave a value of 3×10^{-5} equivalents of amine per gram. The polyamide was dried in a -30°C dewpoint oven for 12–16 h at 71°C before compounding. The PP was a stabilized Amoco isotactic homopolymer with a melt-flow rate of 3.5 g/10 min. The blends were compatibilized with two different relatively low molecular weight isotactic PP-*g*-MA compatibilizers, shown in Table I. The melting temperatures of low-anhydride compatibilizer (LAC) and high-anhydride compatibilizer (HAC) were 4 and 10°C lower than PP, respectively, and both were semicrystalline (Table I). The compatibilizers were vacuum-dried at 100°C for 16 h before compounding.

Molecular weights of the compatibilizers were determined by GPC and the anhydride contents were measured by NMR, FTIR, and titration meth-

Table I Molecular Weight and Thermal Data of Blend Components and Compatibilizers

	PA	PP	LAC	HAC
M_w	29,000	356,000	135,000	52,100
M_n	14,000	71,000	42,500	16,100
T_m (°C)	265.4	164.1	160.4	154.6
% Crystallization	36.2	50.0	38.1	36.0

ods. The LAC had an average of one anhydride group per chain (0.2% anhydride by weight) and the HAC had an average of six anhydride groups per chain (2.7% anhydride by weight). Whereas the LAC had much less grafted anhydride, it also had a molecular weight approximately three times higher than that of the HAC. Both LAC and HAC were characterized by GPC and by FTIR after vacuum drying and also after precipitation from hot xylene into acetone followed by vacuum drying. No difference in molecular weight distribution or grafted anhydride content was found between the nonprecipitated and precipitated samples. The DSC melting behavior was also the same. Therefore, the LAC and HAC were presumed to be randomly grafted and not mixtures of highly grafted oligomer and PP.

Methods

The blend components were compounded in a nitrogen-purged barrel (45/1 L/D) in a Werner-Pfleiderer ZSK-30 extruder at 285°C, dried in a -60°C dewpoint oven, and injection-molded using a multispecimen mold and a temperature of 277°C throughout the barrel. The injection pressure was 16 MPa, the back pressure was 0.34 MPa, and the mold cavity temperature was 65°C. The specimens were then stored in sealed containers with a desic-

cant and dried in a vacuum at 80°C for 3–4 days before testing.

Blend compositions used in this study are listed in Table II. The blends were prepared with the same amounts of compatibilizer, specifically, 2.5, 3.75, 7.5, and 11.25%. Similar anhydride concentrations were achieved by preparing blends with large amounts of LAC (15, 20, and 25%) and small amounts of HAC (0.8, 1.0, and 2.0%). The anhydride concentration in the blends varied differently with compatibilizer loading due to the different amounts of graft anhydride on the LAC and HAC chains. The amount of PP in the blend was adjusted so that PP plus compatibilizer was 75% by weight while the PA remained constant at 25% by weight.

Undeformed blend samples were cryogenically fractured perpendicular to the injection-molding direction after submersion in liquid nitrogen for 1 h. Fracture surfaces were coated with 60 Å of gold and the domain morphology was observed in a JEOL 840A scanning electron microscope. Photomicrographs were taken near the center of the thickness. V-notched (45°) tensile bars were fractured at ambient using a displacement speed of 2 mm/min. The fracture surfaces were coated with 60 Å of gold and microdeformation processes were observed in the scanning electron microscope.

Injection-molded unnotched dogbone specimens

Table II Blend Compositions Showing Compatibilizer and Anhydride Concentrations

PP/LAC/PA	Anhydride (%)	PP/HAC/PA	Anhydride (%)
75.00/0/25	0	75.00/0/25	0
72.50/2.50/25	0.005	74.20/0.80/25	0.022
71.25/3.75/25	0.008	74.00/1.00/25	0.027
67.50/7.50/25	0.015	73.00/2.00/25	0.054
63.75/11.25/25	0.023	72.50/2.50/25	0.068
60.00/15.00/25	0.030	71.25/3.75/25	0.101
55.00/20.00/25	0.040	67.50/7.50/25	0.203
50.00/25.00/25	0.050	63.75/11.25/25	0.304

(Type I ASTM D638) 3.15 mm thick were used to characterize mechanical behavior. Uniaxial tensile tests were conducted at room temperature on an Instron 1123 mechanical testing machine using a strain rate of $5\% \text{ min}^{-1}$. Tensile strength was the maximum stress that was reached, either fracture or yield.

RESULTS AND DISCUSSION

Morphology of PP/PA Blends

The uncompatibilized blend of PP/PA (75/25) had a coarse morphology with domain sizes as large as tens of microns [Fig. 1 (a)]. The large particle size, with no evidence of adhesion between the matrix and dispersed phase, confirmed the incompatibility of the two components. In compatibilized blends, the PA was dispersed in the PP as spherical particles. Addition of 2.5% LAC produced a dispersion of fairly uniform PA particles about $2 \mu\text{m}$ in diameter [Fig. 1 (b)]. The PA particles were even smaller when the blend was compatibilized with 2.5% HAC [Fig. 1 (c)]. It was evident that the compatibilizers affected the PA particle size differently. The PA particles in the blend with HAC also appeared to be more deeply embedded in the matrix.

The PA particle size initially decreased with increasing amount of either compatibilizer, then reached a constant value of about $0.4 \mu\text{m}$ when increasing compatibilizer further had no effect on particle size. However, HAC was more efficient than was LAC in dispersing PA. The plot in Figure 2 shows that the particle size correlated better with the amount of anhydride in the blend, rather than with the amount of compatibilizer. Small concentrations of anhydride had a very large effect on particle size, e.g., 0.03% anhydride decreased the average particle size from over $4 \mu\text{m}$ to less than $1 \mu\text{m}$. Further increases in anhydride concentration, up to 0.3%, resulted in only minimal additional decrease in particle size. Because the anhydride content of HAC and LAC was very different, the smallest amount of HAC used, 0.8%, was sufficient to achieve a PA particle size less than $1 \mu\text{m}$. To achieve a PA particle size less than $1 \mu\text{m}$ with LAC, 11.25% of the compatibilizer was required.

If it is assumed that the graft copolymer is located at the interface between the two phases with complete penetration of the two phases, the interfacial area stabilized per molecule (A) can be estimated by⁶

$$A = \frac{3\Phi M_n}{RW_c N} \quad (1)$$

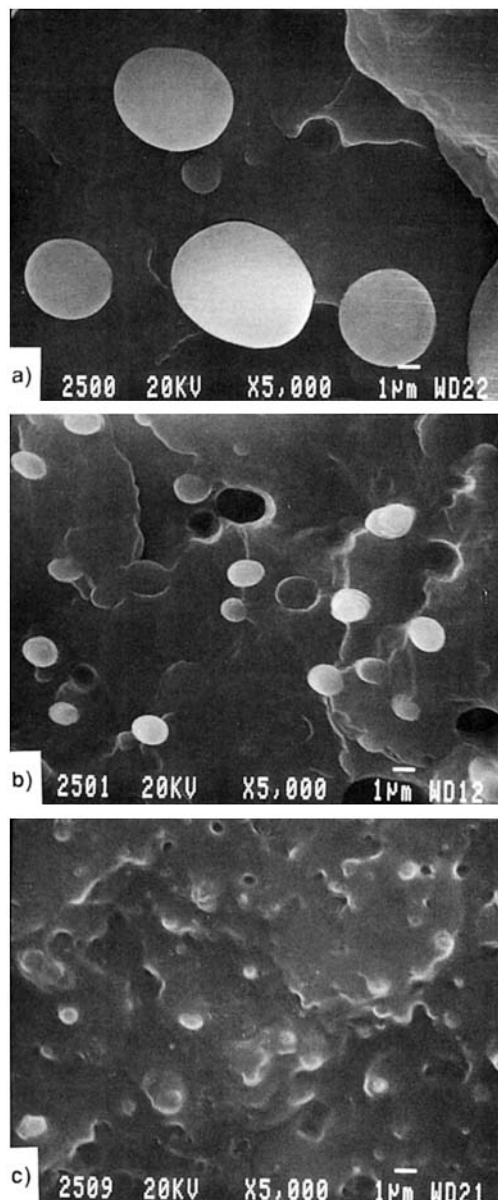


Figure 1 Blend morphology: (a) the uncompatibilized blend (PP/PA:75/25); (b) blend containing 2.5% LAC; (c) blend containing 2.5% HAC.

where Φ is the volume fraction of the dispersed phase; M_n , the number-average molecular weight of the compatibilizer; R , the particle radius; W_c , the mass of compatibilizer per volume of blend; and N , Avogadro's number. The calculated values of surface area stabilized per compatibilizer molecule in Table III were estimates only; a primary source of uncertainty was the use of an average particle size to represent the particle-size distribution.

From the stabilization areas in Table III, it was possible to develop a qualitative picture of LAC and

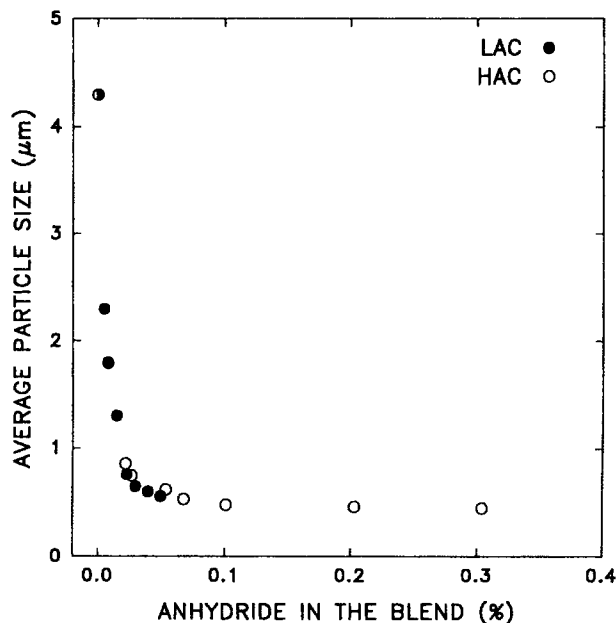


Figure 2 Polyamide particle size as a function of the anhydride concentration in the blend.

HAC distribution and extent of reaction. To begin, it was assumed that with the lowest LAC content (2.5%) all LAC molecules reacted to form block copolymer and were located at the interface [Fig. 3(a)]. The copolymer formed by LAC and PA probably was close to a PP/PA diblock structure. Since most of the compatibilizer chains of LAC had a single terminal anhydride group, coupling of LAC and PA would have occurred predominantly at the chain ends with formation of a diblock copolymer, according to the generally accepted reaction mechanism. The area stabilized per LAC molecule was then taken to be about 180 \AA^2 . The choice of a value slightly greater than 160 \AA^2 was based on other work with the same LAC compatibilizer.¹⁶ A calculated value smaller than 180 \AA^2 was interpreted as less than 100% of the compatibilizer at the interface due to incomplete reaction of the anhydride groups. A value larger than 180 \AA^2 indicated that compatibilizer molecules were spread out on the interface. This was only expected with HAC where on that average there were six anhydride groups per chain that could react. The resulting comb-shaped graft copolymer could have penetrated the interface at several locations. In this case, it was assumed that the interfacial area stabilized per reacted anhydride group was 180 \AA^2 regardless of how many other anhydrides on the HAC molecule were reacted.

The decreasing surface area as the LAC content increased from 2.5 to 7.5% indicated less than com-

plete reaction of the LAC molecules; the unreacted LAC molecules were probably dispersed in the PP matrix. When the LAC content was higher than 7.5%, there was less confidence in the particle-size measurements, while at the same time, small changes in particle size had a large effect on the calculated surface area. For these reasons, differences in calculated surface area per molecule were not considered significant when the LAC content was larger than 7.5%. For these compositions, the stabilized surface area per molecule was taken to be on the order of $90\text{--}100 \text{ \AA}^2$, which suggested that about one-half of the LAC molecules reacted to form copolymer [Fig. 3(b)].

The HAC compatibilizer was more efficient in dispersing PA than was LAC, meaning that the stabilized surface area per molecule was larger, especially when the compatibilizer was present in small amounts. With 0.8% HAC, the surface area stabilized was about three times that of an LAC molecule. This suggested that if all the HAC chains were at the interface each would have, on the average, three grafts penetrating the interface [Fig. 3(c)]. The fraction of reacted anhydride decreased as the HAC content increased. With 3.75% HAC, about one-quarter of the anhydride groups were reacted; this decreased to only one-twelfth with 11.25% HAC.

Although it was not possible to confirm whether some HAC molecules were highly reacted and spread out at the interface while most of the HAC remained

Table III Average Size of Particles and Area Stabilized per Molecule of Compatibilizer

Compatibilizer Content (Wt %)	PP/PA (75/25)					
	LAC			HAC		
	R ^a	D ^b	A ^c	R	D	A
0.80				3.4	0.8	552
1.00				2.7	0.7	566
2.00				1.4	0.6	398
2.50	14.7	2.4	161	1.1	0.5	353
3.75	9.8	1.8	137	0.7	0.4	265
7.50	4.9	1.3	95	0.4	0.4	133
11.25	3.3	0.7	118	0.2	0.4	88
15.00	2.5	0.6	103			
20.00	1.8	0.6	93			
25.00	1.5	0.5	82			

^a R = amine/anhydride ratio.

^b D = particle diameter (μm).

^c A = surface area stabilized per compatibilizer molecule (\AA^2).

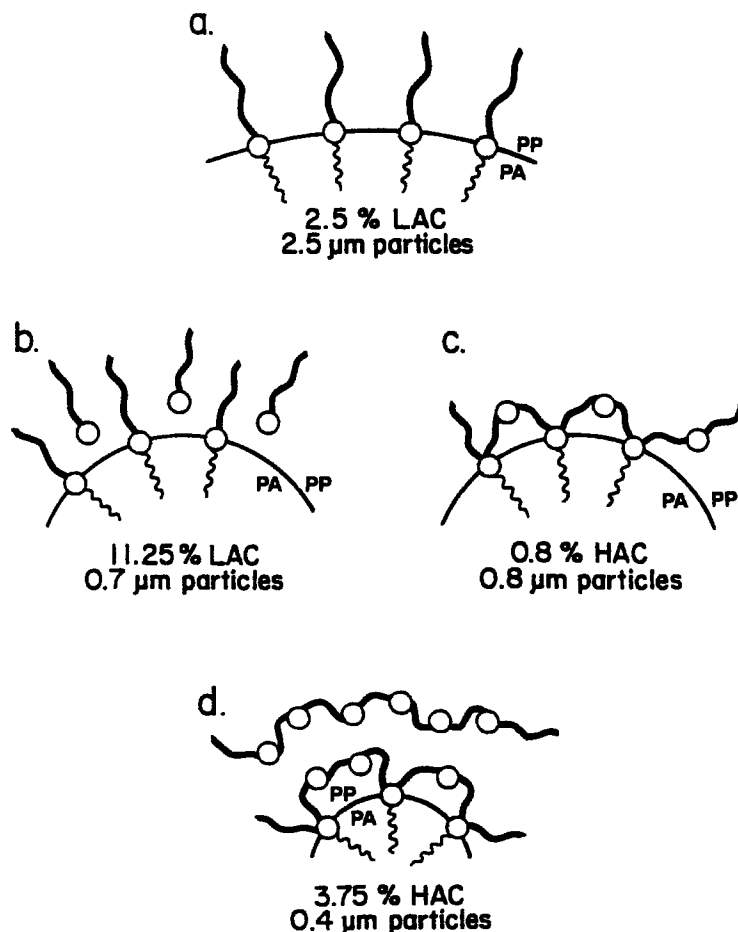


Figure 3 Schematic representation of interface stabilization: (a) 2.5% LAC; (b) 11.25% LAC; (c) 0.8% HAC; (d) 3.75% HAC.

unreacted, or whether the reacted anhydride groups were distributed among the HAC molecules, it was speculated that once an HAC molecule came in contact with a PA particle and one anhydride group reacted the close proximity of the others made it more likely that other anhydride groups on the same molecule would react and the grafted molecule would spread on the interface. The sketch in Figure 3(d) shows schematically the situation with 3.75% HAC where about only one-quarter of the anhydride groups were estimated to be reacted. If half the anhydride groups reacted on a molecule that reached the interface, half the HAC molecules would have been at the interface, while half would have no reacted anhydride groups and would probably have been distributed in the PP matrix.

It was possible that incomplete reaction of anhydride, especially when the compatibilizer content was high, was due to insufficient amine. The amine-to-anhydride ratios are included in Table III. These were calculated without consideration of molecular

weight changes during processing; nevertheless, even taken as estimates, they indicate a large excess of amine groups available for reaction when the LAC content was 2.5%, consistent with the assumption that all the anhydrides were reacted in this composition. The excess amine decreased substantially as the LAC content increased. Even though the amine-to-anhydride ratio was always greater than the one in the blends compatibilized with LAC, including the 25% LAC composition, it seemed likely that some fraction of the PA chain ends were buried in the dispersed phase and would not have been accessible to LAC at the interface.

Since the stabilized surface area depended on the total anhydride in the system, it was more useful to relate the fraction of reacted anhydride to the amine-to-anhydride ratio, rather than to the amount of compatibilizer. Thus, when 0.8% HAC and 11.25% LAC provided about the same total anhydride, with an amine-to-anhydride ratio of about 3.3, the fraction of anhydride reacted was also comparable, about

one-half. Combining the data for LAC and HAC, the fraction of reacted anhydride decreased as the amine-to-anhydride ratio decreased from essentially 100% when the ratio was greater than 10 to about one-third when the ratio was close to 1 (2.5% HAC). The multiple reaction sites and low molecular weight of HAC made it possible to achieve blends with amine-to-anhydride ratios less than 1. When this was the case, the fraction of reacted anhydride was even lower. The three compositions were 3.75% HAC with approximately one-quarter of the anhydrides reacted, 7.5% HAC with one-eighth reacted, and 11.25% HAC where only one-twelfth of the anhydride groups had reacted.

Tensile Behavior of PP/PA Compatibilized Blends

The stress-strain behavior of the control materials, including the uncompatibilized blend, is shown in Figure 4. It is evident that the addition of 25 wt % PA resulted in a reduction in the tensile strength of PP as well as a large reduction in fracture strain. This behavior is typical of incompatible blends with poor interfacial adhesion. If the PA particles behave as voids, thereby reducing the effective cross-sectional area and requiring a lower remote load to achieve the same effective stress, the reduction in tensile strength is given by¹⁷

$$\sigma_v = \sigma_0[1/(1 - 1.2C_v^{2/3})] \quad (2)$$

where σ_0 is the tensile strength of PP, and σ_v , the tensile strength of PP with a void fraction equal to C_v assuming that the voids are spherical and arranged in a cubic array. This calculation predicts that the tensile strength of PP with 25 wt % PA ($C_v = 0.21$) would be reduced by a factor of 0.57. Using the observed tensile strength of PP (33 MPa), the equation predicts that the tensile strength of the uncompatibilized blend with 25 wt % PA would be 19 MPa if the PA particles acted as voids. Since the measured tensile strength was significantly higher, 27 MPa, physical adhesion must have provided some degree of stress transfer to the PA particles.

The addition of compatibilizer increased the tensile strength from 27 MPa in the uncompatibilized blend to 35–38 MPa, which was also higher than the PP control (Figs. 5 and 6). This was attributed to improved adhesion in the compatibilized blends that facilitated stress transfer to the PA particles and increased their load-bearing capacity. Tensile strength of the LAC-compatibilized blends decreased gradually from 38 to 35 MPa with increasing compatibilizer, while all the blends with HAC had about the same strength (35 MPa). The maximum tensile strength of 25 wt % PA blends with good adhesion was predicted using Nielsen's equation for the yield strain¹⁸:

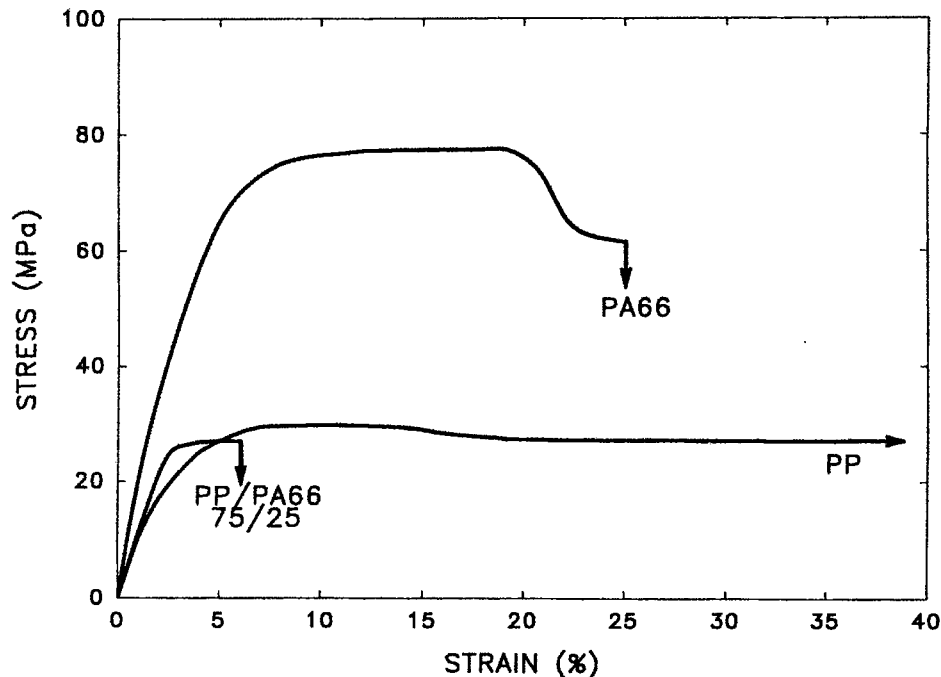


Figure 4 The stress-strain behavior of the control materials: PA, PP, and PP/PA (75/25).

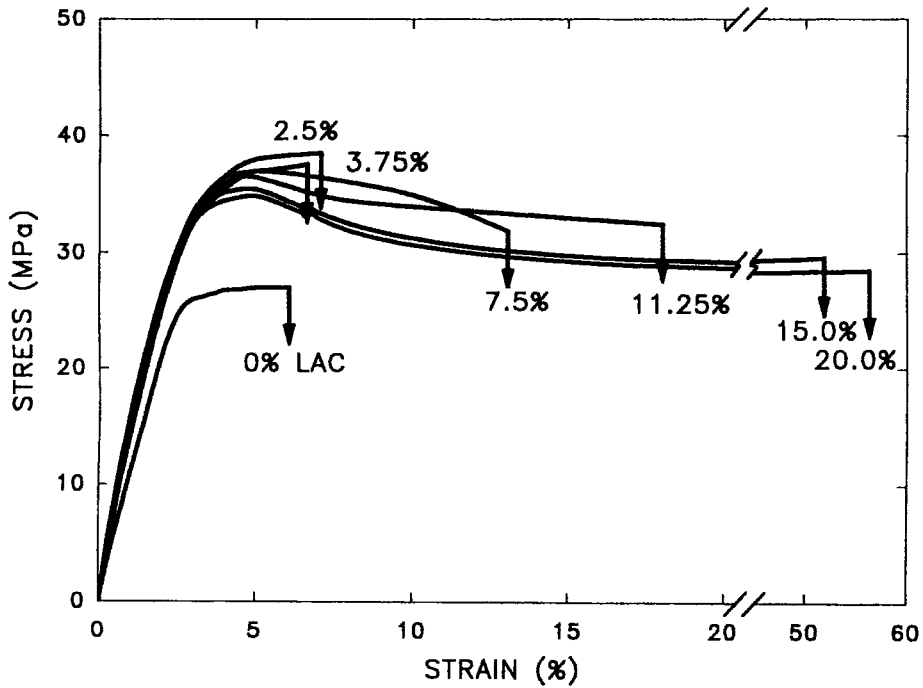


Figure 5 Stress-strain curves of blends compatibilized with LAC containing increasing loadings of compatibilizer: 2.5, 3.75, 7.5, 11.25, 15.0, and 20.0%.

$$\epsilon_{yblend} = \epsilon_{yPP} (1 - a\Phi_{PA}^{1/3}) \quad (3)$$

where ϵ_{yPP} is the yield strain of PP; Φ_{PA} , the volume fraction of PA; and a , a geometric factor associated

with the yielding angle around a spherical PA particle. After the yield strain of the blend, ϵ_{yblend} , was obtained from eq. (3), the tensile strength was calculated using the modulus of a blend with good

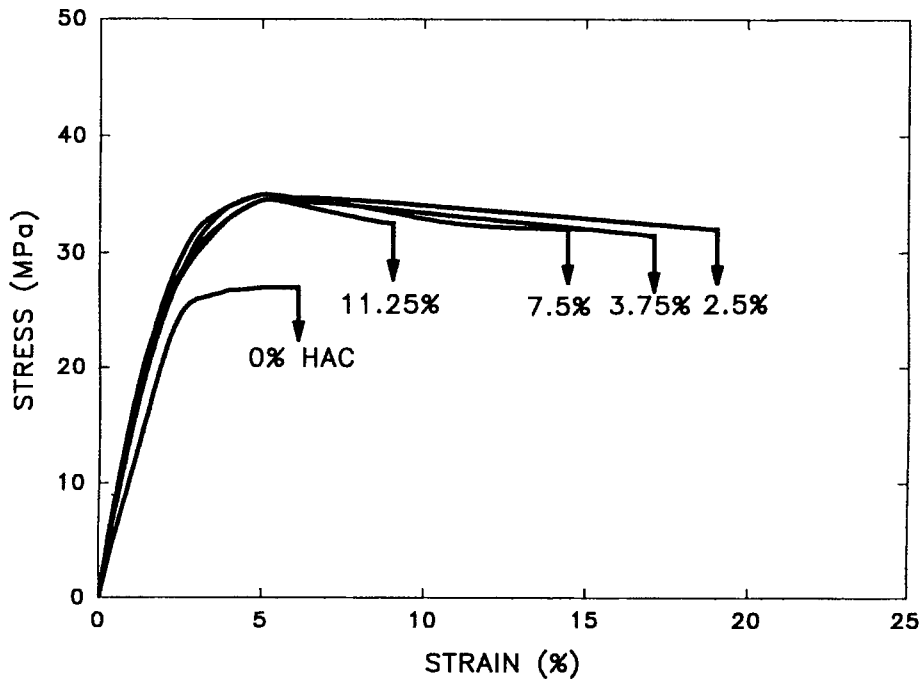


Figure 6 Stress-strain curves of blends compatibilized with HAC containing decreasing loadings of compatibilizer: 11.25, 7.5, 3.75, and 2.5%.

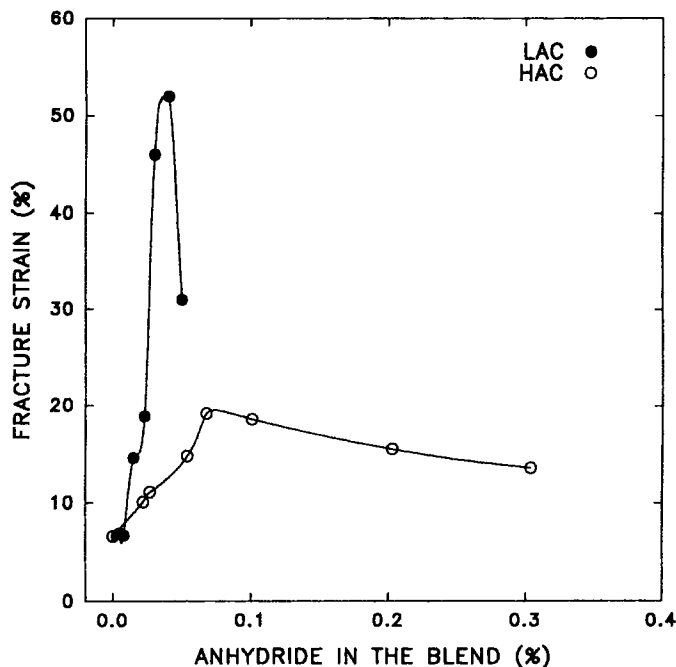


Figure 7 Fracture strain in the blends as a function of the anhydride concentration in the blend.

adhesion. The predicted maximum tensile strength for blends with good adhesion was 40 MPa, slightly higher than the observed values.

Although compatibilization with either LAC or HAC produced about the same increase in tensile strength, their effect on fracture strain was not the same either in terms of the trend in the fracture strain with increasing compatibilizer content or in terms of the magnitude of the fracture strain that was achievable with compatibilization. The fracture strain of blends with LAC increased from 7% with 2.5% LAC and to 56% with 20% LAC when the blend necked before fracturing. In contrast, the highest fracture strain with HAC was only 19% and was achieved with 2.5% compatibilizer. Increasing the HAC content above 2.5% resulted in a gradual decrease in the fracture strain.

The fracture strain is plotted in Figure 7 as a function of anhydride concentration in order to make comparisons with the corresponding plot of particle size (Fig. 2). The maximum fracture strain occurred at a similar anhydride concentration for the LAC and HAC blends: 0.040% for LAC and 0.068% for HAC. Approximately the same anhydride concentration was required to achieve a particle size of 0.5 μm . Figure 7 also shows several compositions that compare similar anhydride concentrations achieved by high loadings of LAC and low loadings of HAC. The blends containing LAC achieved sig-

nificantly higher fracture strains than those containing HAC. The improvement in mechanical properties with both compatibilizers was attributed to the reduction in particle size and improved adhesion by the graft copolymer that formed a chemical linkage across the matrix-particle interface. However, it appeared that LAC improved fracture strain to a greater degree than HAC; this was attributed to differences in adhesion since particle sizes were similar.

Interfacial Deformation

Evidence for differences in adhesion was sought by examining interfacial deformation on notched tensile fracture surfaces of LAC- and HAC-compatibilized blends. Deformed material on the fracture surfaces was PP and possibly the compatibilizer, whereas the PA particles remained undeformed regardless of how good the adhesion was because the yield stress of PA was significantly higher than the fracture stress of the blends. Fracture surfaces of the 11.25% LAC blend in Figure 8 showed the PA particles enmeshed in a highly drawn network of matrix material. Numerous thin ligaments connected PA particles to the deformed matrix and incorporated the particles into the fibrous PP network. This evidence that particle-matrix adhesion was good enough to prevent debonding during matrix

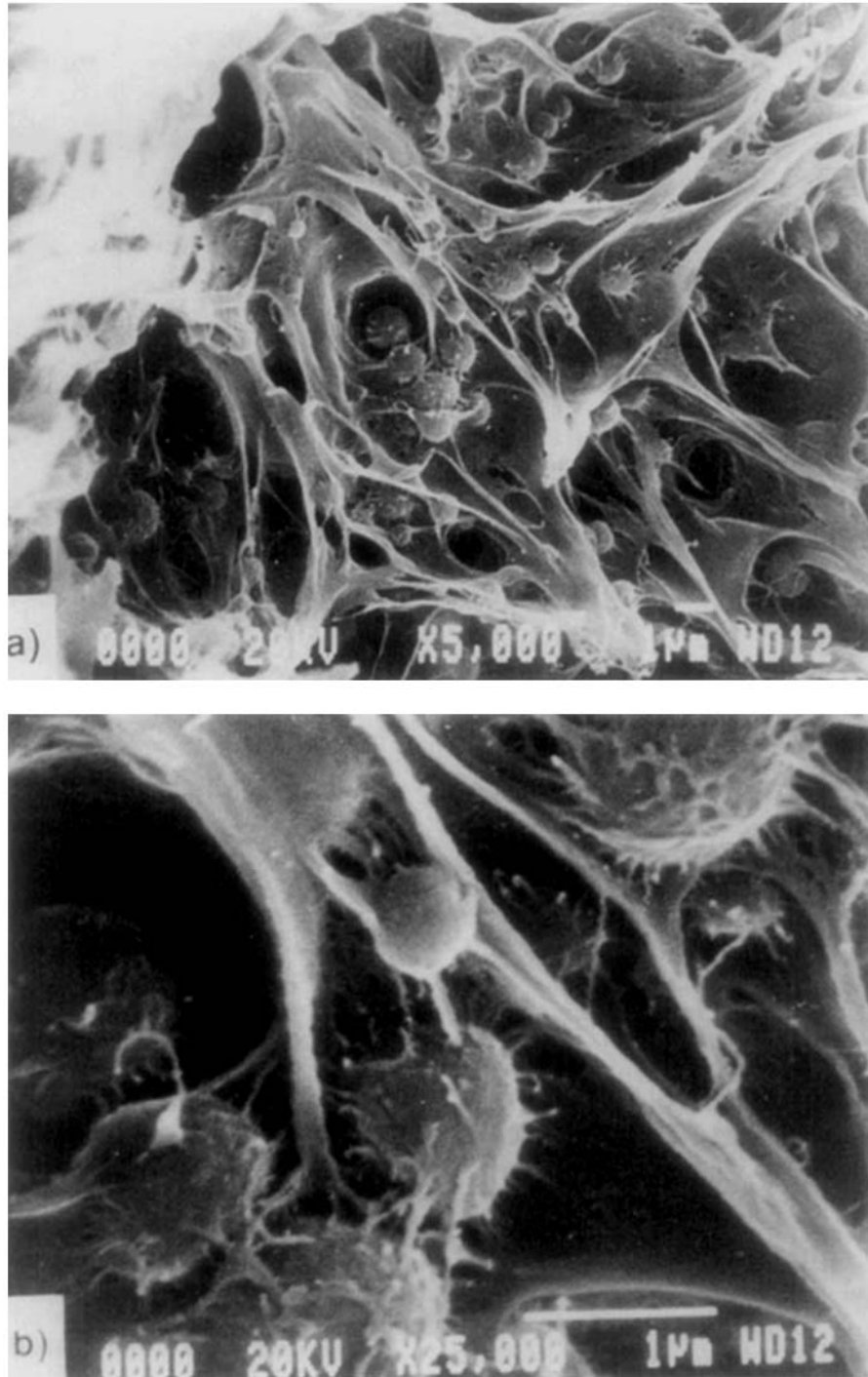


Figure 8 Fracture surface of 11.25% LAC blend showing microscale deformation near PA particles at two magnifications: (a) 5000 \times ; (b) 25,000 \times .

drawing indicated that the interfacial strength was higher than the fracture strength of the matrix. The ribbonlike features on the drawn ligaments were the result of recoil after they fractured.

Fracture surfaces of the 11.25% HAC blend in

Figure 9 showed tufts of matrix material pulled out between clusters of PA particles and only occasionally were there thin ligaments attaching the PA particles to the pulled-out tufts. The residual material that gave the particles a rough texture was believed

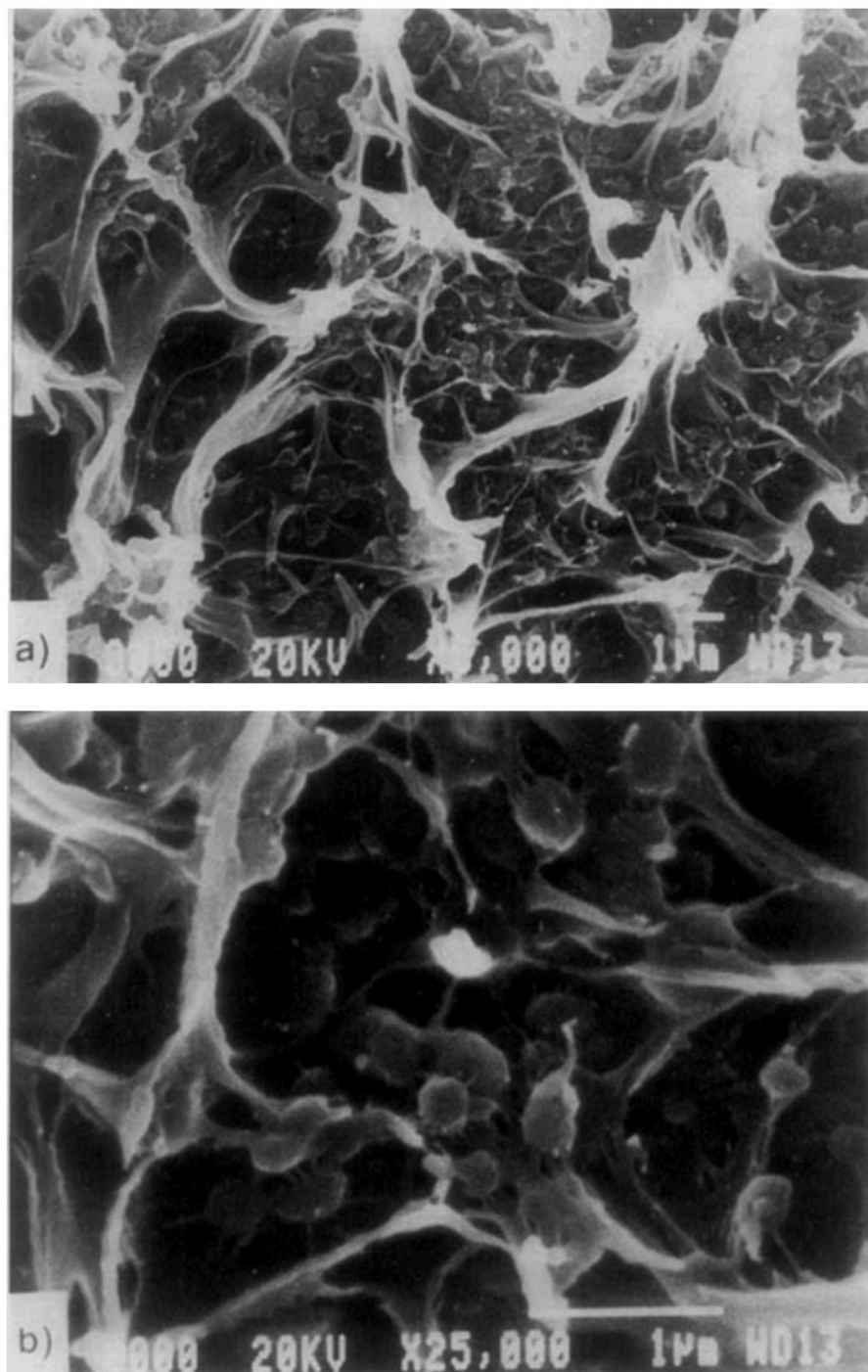


Figure 9 Fracture surface of 11.25% HAC blend showing microscale deformation near PA particles at two magnifications: (a) 5000 \times ; (b) 25,000 \times .

to include compatibilizer left by the interfacial failure. Thus, it appeared that the interfacial strength provided by HAC was lower than the draw stress of PP.

The blend strength was similar in HAC and LAC blends because adhesion was maintained until the

matrix yielded. The better adhesion provided by LAC was manifest primarily in the ultimate elongation. It was presumed that interfacial strength in the blends was determined primarily by interaction of the compatibilizer with PP, since adhesion to PA was provided by chemical linkages. The interaction

of LAC with PP was strong enough to sustain particle-matrix adhesion as the compatibilizer was drawn along with the PP. This translated on the macroscale into higher fracture strains for the LAC blends. Interaction of HAC with PP was not strong enough to sustain adhesion with the PA particles when the matrix began to draw. Therefore, drawing occurred only in the matrix-rich regions between debonded particles and, consequently, the drawn PP appeared as tufts rather than as a network. Interfacial failure produced voids that subsequently became the sites for crack initiation and ultimately lower fracture strains.

CONCLUSIONS

A low-anhydride compatibilizer and a high-anhydride compatibilizer both improved the dispersion of polyamide-66 (PA) in polypropylene (PP). The PA particle size was determined by the anhydride concentration rather than the amount of compatibilizer. Thus, less than 1 wt % of the high-anhydride compatibilizer (HAC) produced an average particle size less than 1 μm , whereas more than 11 wt % of the low anhydride compatibilizer (LAC) was required to achieve a similar particle size. Estimates of the interfacial area stabilized per compatibilizer molecule suggested that the fraction of anhydride groups reacted with amine to form copolymer decreased significantly as the anhydride content increased.

The tensile strength of the uncompatibilized blend was lower than that of PP due to poor adhesion between the phases. With improved adhesion, the tensile strength of the compatibilized blends was about twice that of the uncompatibilized blend and was also higher than that of PP. The tensile strength of the compatibilized blends was relatively unaffected by the amount of compatibilizer or by whether the low or high anhydride compatibilizer was used.

Maximum fracture strain was obtained with similar anhydride content; however, a much higher maximum fracture strain was achieved with LAC than with HAC. During matrix drawing, the PA particles in the LAC-compatibilized blends remained connected to the matrix by thin ligaments, whereas interfacial failure occurred in the HAC-compatibilized blend as the matrix was drawn out. It was proposed that interaction of the compatibilizer with PP

was responsible for the difference in interfacial strength.

The authors wish to thank the Amoco Chemical Co. for financial support of this work and for supplying the materials. The Amoco Corporate Research Laboratory provided FTIR, NMR, and titration analyses of the compatibilizers. Titration of the polyamide for amine end groups was performed by R. Keske of Amoco Performance Products, Inc. Polymer blend extrusion, molding, and purification of analytical samples were performed by members of the Polymer Applications Group, especially by M. Wreschinsky.

REFERENCES

1. A. R. Shultz and B. M. Gendron, *J. Appl. Polym. Sci.*, **16**, 461 (1972).
2. J. Stoelting, F. E. Karasz, and W. J. Macknight, *Polym. Eng. Sci.*, **10**, 133 (1970).
3. H. Suarez, J. W. Barlow, and D. R. Paul, *J. Appl. Polym. Sci.*, **29**, 3253 (1984).
4. T. Kurauchi and T. Ohta, *J. Mater. Sci.*, **19**, 1699 (1984).
5. M. Xanthos, *Polym. Eng. Sci.*, **28**, 1392 (1988).
6. D. R. Paul, in *Polymer Blends*, D. R. Paul and S. Newman, Eds., Academic Press, New York, 1978, Vol. 2, pp. 35-62.
7. N. Gaylord, *J. Polym. Sci. Polym. Lett. Ed.*, **20**, 481 (1982).
8. N. Gaylord, *J. Polym. Sci. Polym. Lett. Ed.*, **21**, 23 (1983).
9. F. Ide and A. Hasegawa, *J. Appl. Polym. Sci.*, **18**, 963 (1974).
10. S. Hosoda, K. Kojima, Y. Kanda, and M. Aoyagi, *Polym. Networks Blends*, **1**, 51 (1991).
11. S. J. Park, B. K. Kim, and H. M. Jeong, *Eur. Polym. J.*, **26**, 131 (1990).
12. P. Scholz, D. Froelich, and R. Muller, *J. Rheol.*, **33**, 481 (1989).
13. Z. Liang and H. L. Williams, *J. Appl. Polym. Sci.*, **44**, 699 (1992).
14. C. C. Chen, E. Fontan, K. Min, and J. White, *Polym. Eng. Sci.*, **28**, 69 (1988).
15. I. Park, J. W. Barlow, and D. R. Paul, *J. Polym. Sci. Polym. Phys.*, **30**, 1021 (1992).
16. J. Duvall, C. Sellitti, V. Topolkaev, C. Myers, A. Hiltner, and E. Baer, to appear.
17. O. Ishai and L. Cohen, *J. Comp. Mater.*, **2**, 302 (1968).
18. L. Nielsen, *J. Appl. Polym. Sci.*, **10**, 97 (1966).

Received September 24, 1993

Accepted October 5, 1993