

Study on Compatibilization of Polypropylene–Liquid Crystalline Polymer Blends

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ABSTRACT: The mechanical properties, melt rheology, and morphology of binary blends comprised of two polypropylene (PP) grades and two liquid crystalline polymers (LCP) have been studied. Compatibilization with polypropylene grafted with maleic anhydride (PP-*g*-MAH) has been attempted.

A moderate increase in the tensile moduli and no enhancements in tensile strength have been revealed. Those findings have been attributed to the morphology of the blends, which is predominantly of the disperse mode. LCP fibers responsible for mechanical reinforcement were only exceptionally evidenced. Discussion of PP–LCP interfacial characteristics with respect to mechanical properties–morphology interrelations allowed evaluation of the compatibilizing efficiency of PP-*g*-MAH. Factors important for successful reinforcement of PP with LCP have been specified. © 1997 John Wiley & Sons, Inc. *J Appl Polym Sci* **66**: 969–980, 1997

Key words: polymer blends; mechanical properties; melt rheology; morphology; interfacial tension

INTRODUCTION

The growing demand of industry for plastic materials of specific properties has led to enormous development of materials engineering and science over the past three decades. Because of the rather limited number of new monomers offered for polymerization, remarkable progress has been noted in the modification of processing methods, especially, in the modification of polymers by blending and alloying with other polymeric components.^{1–4}

Polymer blends offer a favorable route to new polymeric materials because of the relative simplicity in blending commercial polymers, as compared to rather the complex and costly way of

getting new polymers by the synthesis. Most polymer pairs are immiscible at the molecular level; thus, they show multiphase characteristics for thermodynamic reasons. Heterogeneous blends are generally preferred over miscible ones since one can not only take advantage of the useful properties of each component, but also find synergism, which results in unusual characteristics of the plastic material. However, polymer blends quite often have poor mechanical properties because of high interfacial tension, which promotes segregation and poor adhesion between the components. Obviously, the commercial application of such blends is restricted for that reason.

Therefore, many polymer pairs have been compatibilized by the addition of a third component, such as block or graft copolymers, which possess segments capable of interactions with each blend component. Such copolymers behave as macromo-

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lecular emulsifiers, providing polar bonds that strengthen and stabilize the blend interface.⁵⁻¹⁴ It has been shown that block and graft copolymers can be also generated *in situ* while blending. Thus, reactive compatibilization, which produces chemical links between the phases, has focused considerable interest in recent years.¹⁵⁻²⁴

In depending on the methods or products used, compatibilization is designed to perform the following:

- (1) reduce the interfacial energy between the phases;
- (2) permit a finer dispersion during mixing;
- (3) provide a measure of stability against segregation;
- (4) improve the interfacial adhesion.

The resulting alloys exhibit usually a desirable property balance.

Among the growing array of polymer blends, the substantial group form thermoplastic composites based on blends of liquid crystalline polymers (LCP) with thermoplastics. LCPs exhibit remarkable properties, like high strength, chemical resistance, low melt viscosity, and low thermal expansion. In general, they have high melting temperatures because of their high enthalpy change and low entropy change at the crystal-to-nematic transition. The nematic structure of thermotropic polymer that causes its self-reinforcing behavior has been one of the leading ideas in a concept of *in-situ* composites. Blends consisting of a thermoplastic matrix and thermotropic LCP do not wear machinery surfaces during processing, in contrast to most traditional composites, containing glass or carbon fibers as a reinforcement. In addition, the composites formed *in situ* have been much easier processable when compared to the compounding and processing of the thermoplastic composites with solid reinforcing agents.

The morphology of polymer blends depends on several factors, among which the blending conditions, blend composition, viscosity ratio, and interfacial tension between components are the most important.²⁵⁻³⁰ The formation of the oriented LCP fibrils from drops is strongly influenced by the flow field. An uniaxial extensional flow field is very effective in bringing about molecular orientation within LCP the phase.³¹⁻³⁸ Nevertheless, the fiber formation under shear flow has been also reported.^{39,40} The morphology and the resulting physical properties are also influenced by the interaction between LCP and the matrix polymer.

If polymers are highly compatible, then the LCP domains will be dispersed too finely to deform into fibers. On the other hand, the lack of compatibility leads to deterioration of mechanical properties, even if fibrils are generated. Poor interfacial adhesion causes that transmission of the mechanical energy through a composite to proceed at the interfaces, making failure of the material to occur easily. Therefore, compatibilization of thermoplastic LCP composites has been an area of considerable interest to researchers in the last few years.⁴¹⁻⁵²

As far as the polymer pairs involved is concerned, most of the work to date has focused on melt blending of commercial thermotropic copolyesters with engineering thermoplastics since their processing temperature range is comparable.^{18,24,38,44,53-59} Blending LCPs with commodity resins in the same extruder becomes difficult, owing to degradation of the matrix polymer or insufficient development of the fibrillar structure of the LCP.

Polypropylene (PP) is one of the most largely consumed polyolefines in the plastics industry because of its durability, easy processability and economy, when compared to engineering thermoplastics. The range of applications for PP may be considerably broadened by modification *via* blending with inorganic fillers, rubbers, or other polymers.^{8,60-67} The main field of interest is the enhancement of impact resistance and tensile properties. Reinforcement of polypropylene with LCP has been attempted recently by several researchers, even if the melting point of PP (165°C) is far below that of aromatic copolyesters, like Vectra A900 (280°C).

Although PP-LCP blends exhibited improvements in moduli values, they show little or no improvement in tensile strength values compared with pure PP. The overall tensile strength was generally less than that of PP, which, in addition with a less-than-expected tensile modulus, suggested incompatibility between components.^{60,68,69}

Compatibilization of PP-LCP blends has been investigated by several researchers. Due to non-polar nature of PP in contrast to the more polar liquid crystalline polymers, attempts have been made with functionalized PP as a compatibilizer. Grafting with reactive monomers is expected to enhance the hydrophilicity of polyolefines.⁷⁰⁻⁷⁷ It is believed that the grafted polar groups, while interacting with respective LCP-blocks link the compatibilizer with a liquid crystalline polymer,

whereas the main chain is entangled with the matrix.

Maleic anhydride (MAH) is a highly reactive monomer used frequently for radically initiated functionalization of polypropylene. MAH molecules grafted onto PP not only increase its polarity, but can also react with respective groups (e.g., $-\text{NH}_2$, $-\text{OH}$, and $-\text{COOH}$) of other polymers, thus forming chemical links between components.

The effect of maleic anhydride grafted with polypropylene (PP-*g*-MAH) on the properties and morphology of the PP-LCP polymer blends was reported in several articles within last three years.^{46,48-50} It was found that the modulus and strength were significantly increased in compatibilized blends. The reinforcing LCP fibrils were found to be much more finely dispersed in the matrix. Moreover, the surface of the moulded samples was much smoother in the presence of PP-*g*-MAH. Thus, the PP-*g*-MAH has been proven as an effective compatibilizer for PP-LCP blends comprised of both copolyesteramide and/or copolyester systems.

Other attempts with PP functionalized with acrylic acid and ethylene-based terpolymers exhibited a pronounced compatibilization effect upon PP blends.^{21,47}

Nevertheless, there are still several unanswered questions remaining as to the effect of compatibilizers on the mechanical properties and morphology of PP-LCP systems, as well as to the nature of interactions between the components.

Our objective is to investigate whether compatibilization with PP-*g*-MAH leads to enhancements in mechanical properties of PP-LCP in every case. The LCP used here is Vectra A950, which is an aromatic copolyester and semirigid terpolyester SBHN. The spacing of rigid backbone molecules with flexible groups was expected not only to depress the melting temperature of the LCP but also to make the polymer more compatible with PP than the wholly aromatic Vectra.^{41,47,55,78-82}

EXPERIMENTAL

Materials

The matrix polymer was PP of two grades: X30G (PP1) and D60P (PP2), supplied by Montell, Italy. According to the manufacturer, the first polymer is characterized by M_w of 270,000 g mol, M_w/M_n of 7.0, and a melt flow index of 12.4 g 10 min.

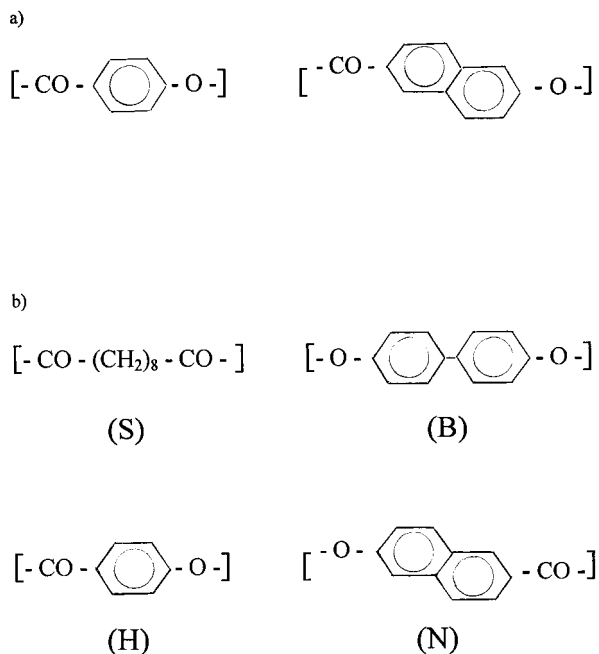


Figure 1 Chemical structures of constituent blocks of the LCP: (a) Vectra A950; (b) SBHN.

Polypropylene D60P has a M_w of 680,000 g mol, M_w/M_n of 9.7, and MFI of 0.39 g 10 min.

Two thermotropic LCP were used for this study. These were Vectra A950 (LCP1) from Hoechst Celanese, USA, and semirigid SBHN 1 : 1 : 3 : 5 (LCP2) produced by Eniricerche S.p.A., Italy (Fig. 1).

Vectra A950 is the wholly aromatic copolyester synthesized from 6-hydroxy-2-naphtic acid (70%) and *p*-hydroxybenzoic acid (30%). Its melting temperature is around 280°C.

The figures in a description of the semirigid SBHN indicate the relative amounts of the units derived from sebacic acid (S), 4,4'-dihydroxybiphenyl (B), 4-hydroxybenzoic acid (H), and 2-hydroxy-6-naphtic acid (N). The melting point of SBHN 1 : 1 : 3 : 5 is ca. 205°C.

The compatibilizing agent was a grafted copolymer PP-*g*-MAH with 1.0 wt % of maleic anhydride, from Montell, Italy.

Additionally, in some experiments, titanium tetrabutoxide was added, for which the catalytic efficiency for a chemical reaction between PP-*g*-MAH and LCP was investigated.

Blends Preparation

PP-LCP blends of 90 : 10 and 80 : 20 by weight were prepared. The compatibilized blends com-

prised an additional 4 phr of a graft copolymer. The polymers were dried in a vacuum oven at 100°C for 24 h before use.

Two methods of blend preparation were applied. The first was kneading for 5 min in a Brabender Plasti-Corder mixing chamber at 290°C, 60 rpm, followed by a compression molding into sheets.

Another method was mixing in a Brabender single screw extruder ($d = 19$ mm, $l : d = 25$ mm) equipped with a rectangular die with a convergent entrance and a drawing unit for straining the ribbon to a draw ratio of ca. 3. Mixing temperature was 290°C and, additionally, 240°C for the SBHN blends.

Measurements

Rheological properties were evaluated both in the dynamic and steady state. Melt flow was measured with the Rheoscope 1000 (CEAST) capillary viscometer, using a capillary of 1 mm diameter, with $l : d = 40$ at 290 and 240°C. The data were corrected according to Rabinowitch, whereas the Bagley correction was neglected due to the high $l : d$ ratio.

Frequency sweep dynamic tests were performed with a plate-plate rheometer RDA II (Rheometrics), at 240°C.

Mechanical properties were determined for strips of 5 mm width, cut out of the compression molded sheets or extruded ribbons, along and transverse to the flow direction. Tensile tests were performed with Instron 1122 apparatus at an elongational rate of 20 mm/min.

Morphological studies were performed on cold-fractured specimens coated with gold. A Philips SEM 505 scanning electron microscope was used for observations of the fractured surfaces.

RESULTS AND DISCUSSION

Comparison of Mixing Equipment

The blends of PP X30G with LCP were prepared both in the Brabender mixer and extruder. Mechanical properties of the blends have been presented in Table I.

The mechanical property enhancements did not occur for the blends prepared in a mixer. Tensile moduli (E) are of similar values, whereas a decrease in the tensile strength (σ) and ultimate elongation (ϵ) has been noted. Low elongation of PP-LCP blends was expected since, in general, the addition of LCP changes the material response from ductile to brittle. However, virgin PP is normally very ductile, with an elongation at the break, which is several orders of magnitude higher than that observed in our test. Such unusual behavior suggests structural changes in the polymer. This has been confirmed with the results of melt rheology (Fig. 2), which have revealed dramatic decrease in the PP1 melt viscosity after processing at 290°C. PP is known to undergo rapid degradation under thermomechanical stress, with a drastic reduction of the molecular weight.⁸³ Again, the melt viscosity is strongly influenced by the structure and, in particular, by the molecular weight of the polymer.

One possible explanation is that PP1 as a polymer composed of relatively short macromolecules underwent extensive degradation under processing at 290°C (mixing followed by press molding), which resulted not only in a decrease in the molecular weight but possibly in some degree of crosslinking as well. Reactions between radicals of PP can occur during degradation and are advantageous, if controlled, for reactive extrusion.⁸⁴ Some extent of crosslinking can explain

Table I Mechanical Properties of PP1-LCP 90 : 10 Blends

Blend/Alloy Content	Mixer			Extruder					
	E (GPa)	σ (MPa)	ϵ (%)	E^{II} (GPa)	E^{I} (GPa)	σ^{II} (MPa)	σ^{I} (MPa)	ϵ^{II} (%)	ϵ^{I} (%)
PP1	1.16	30.9	7	1.16	1.14	29.6	29.3	11	7
PP1-LCP1	1.13	28.2	6	1.51	1.58	29.5	27.2	10	8
PP1-LCP1-comp.	1.16	26.0	4	1.71	1.81	33.1	32.0	7	7
PP1-LCP1-comp.-catal.	1.19	29.0	6	—	—	—	—	—	—
PP1-LCP2	1.06	14.1	3	1.53	1.48	29.6	27.2	11	7
PP1-LCP2-comp.	1.12	24.6	5	1.32	1.30	28.0	24.0	9	7
PP1-LCP2-comp.-catal.	1.11	21.2	3	—	—	—	—	—	—

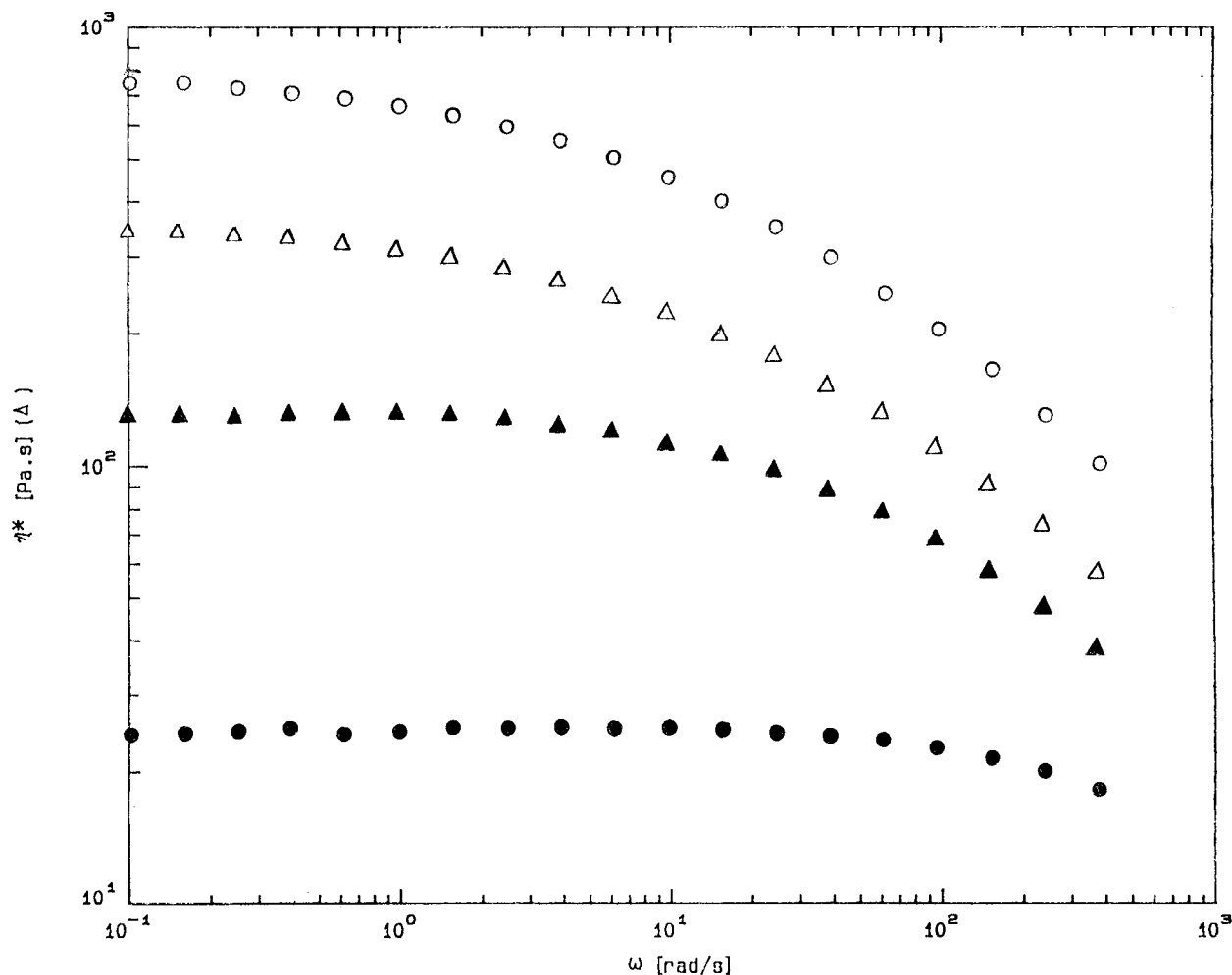


Figure 2 Flow curves (measured at 240°C) of polypropylene PP1 subjected to different thermomechanics: ○, as supplied; △, press moulded at 290°C; ▲, extruded at 290°C; ●, kneaded in a Brabender mixer at 290°C.

both the low values of elongation at the break and the higher tensile modulus of PP1 than PP2 (Table II).

Comparison of the technologies for the sample preparation has revealed that the mechanical properties of PP-LCP blends prepared by extrusion are superior than that prepared in internal mixer. This conclusion concerns both LCP grades, but particular improvement has been observed for blends with Vectra A950. PP1-LCP1 systems show increase in moduli of 30% and of 50% after compatibilization. Tensile strength of the blends shows increase of 15% only after addition of PP-*g*-MAH, thus confirming enhancement of interfacial adhesion. The improvement of mechanical properties observed for extruded blends can be attributed both to the favorable extensional flow field developed while processing and to a lower thermo-

mechanical stress. Blends prepared in the mixer underwent intensive shear for 5 min, whereas residence time in the extruder was only 1 min, which is of particular importance for the very degradation-sensitive matrix polymer.

Nevertheless, PP-grade X30G has to be evaluated as a polymer ineligible for modification with majority of LCP because of its instability at temperatures beyond the crystal-to-nematic transition of LCP. It can be reinforced, though, with LCP, either using novel processing methods like the dual-extruder mixing method⁸⁵ or novel LCP of low melting temperatures.

Mechanical Properties

Polypropylene D60P, as a high-molecular-weight polymer, was much less degraded; therefore, its

Table II Mechanical Properties of Extruded PP2-LCP Blends

Blend-Alloy Content	E^{II} (GPa)	E^{I} (GPa)	σ^{II} (MPa)	σ^{I} (MPa)	ϵ^{II} (%)	ϵ^{I} (%)
PP2	0.94	0.86	36.7	30.7	1163 ^a	836 ^a
PP2-LCP1 90 : 10	1.37	0.74	36.3	19.6	23	13
PP2-LCP1 90 : 10 comp	1.35	1.05	36.9	27.9	14	12
PP2-LCP1 90 : 10 comp-catal.	1.29	1.04	34.6	24.7	9	19
PP2-LCP2 90 : 10	1.26	1.24	27.6	19.3	468 ^a	5
PP2-LCP2 90 : 10 comp	1.42	1.17	9.1	25.0	79	7
PP2-LCP2 90 : 10 comp-catal.	1.14	1.06	27.3	23.0	27	6
PP2-LCP2 80 : 20 comp	1.47	1.56	32.6	13.0	11	3
PP2-LCP2 80 : 20 comp-catal.	1.58	0.88	31.0	15.1	9	6

^a Fibrillation.

blends have been interpreted in terms of LCP and the compatibilizer influence (Table II). Ductile character of PP2 has been preserved even after extrusion at 290°C.

The addition of 10% LCP1 resulted in the modulus enhancement of ca. 45% in a direction of extrusion (II), in contrast to that of transverse direction (I), which decreased of 15%. Similarly, the tensile strength in that direction is markedly lower than that in the flow direction. These findings confirm anisotropy of PP2-LCP1 blends after extrusion.

Compatibilization with PP-*g*-MAH gives rise to an increase in the modulus and tensile strength in a direction perpendicular to extrusion. These properties were not affected by the addition of the adhesion promotor (Ti-salt). Failure of all blends occurred in a brittle manner, typical of the LCP phase.

A similar conclusion concerns PP2-LCP2 blends, although the elongation at the break of the samples machined in a direction transverse to flow was depressed in several orders of magnitude in comparison to PP2, reaching more than a 250-fold decrease for compatibilized blend with 20% of LCP2. Ultimate elongation in perpendicular direction decreased stepwise in the following order: PP2-LCP2; PP2-LCP2-PP-*g*-MAH; PP2-LCP2-PP-*g*-MAH-catalyzer. A further decrease in elongation occurred after an increase in the LCP content up to 20%.

The tensile modulus of PP2-LCP2 blends shows an increase of 30% in comparison to the unmodified polymer. Compatibilization gives rise to a further enhancement of ca. 50%. The highest modulus (70% increase) has been observed for the blend PP2-LCP2-PP-*g*-MAH-catalyzer.

The tensile strength of PP2 deteriorated after

the addition of 10% LCP of ca. 25%. Further increase of the LCP2 content up to 20% resulted in a slight improvement of tensile strength, which was still ca. 10% below that of PP2 itself. Anisotropic character of extruded PP2-LCP2 blends has been distinctly revealed in the tensile tests.

Melt Rheology

LCP led to a significant decrease in PP melt viscosity, measured with a capillary rheometer (Fig. 3). The influence is proportional to the LCP content. Compatibilization with PP-*g*-MAH caused an additional decrease in the melt viscosity.

More pronounced effect of SBHN on PP blends extrudability has been attributed to much lower viscosity of this LCP in comparison to that of Vectra A950.

A slight increase in the melt viscosity of com-

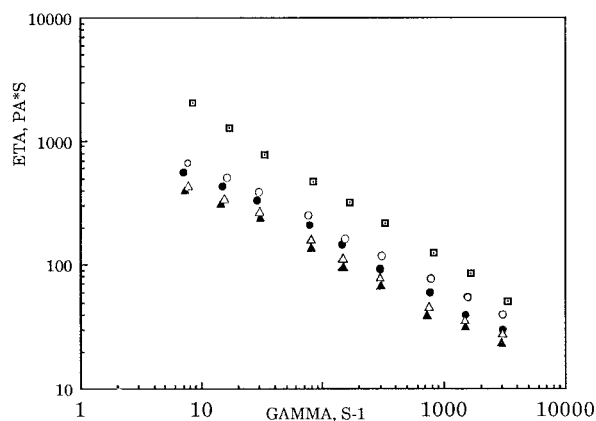


Figure 3 Flow curves of PP-LCP 90 : 10 blends and alloys by capillary rheometry (290°C): \square , PP2; \circ , PP2-LCP1; \bullet , PP2-LCP1-comp; \triangle , PP2-LCP2; \blacktriangle , PP2-LCP2-comp.

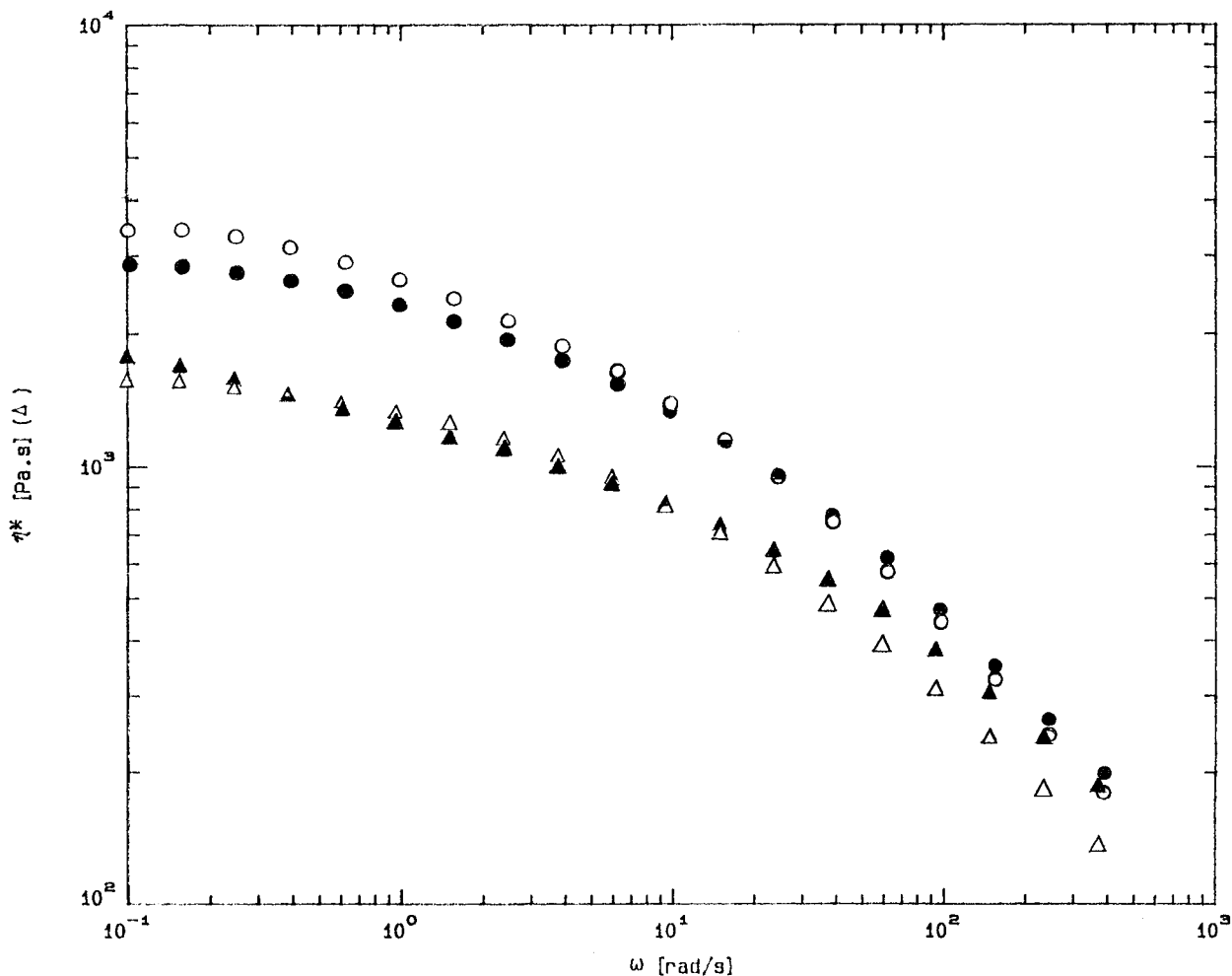


Figure 4 Melt viscosity of PP-LCP alloys by the oscillatory method (240°C): ○, PP2-LCP1 90 : 10 comp-catal.; ●, PP2-LCP1 90 : 10 comp; △, PP2-LCP2 80 : 20 comp-catal.; ▲, PP2-LCP2 80 : 20 comp.

patibilized PP-LCP blends after addition of an adhesion promoter was evidenced at low shear rates by means of oscillatory shear experiments (Fig. 4). This finding suggests an enhanced interfacial adhesion between the phases caused by the catalyzer. This effect may be attributed to enhanced interactions between the maleic anhydride and polar groups of the LCP.

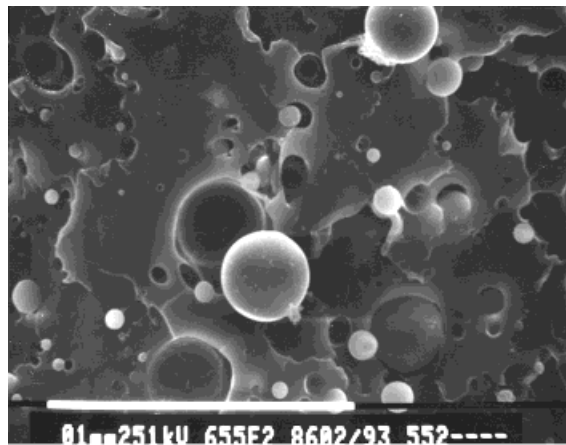
The LCP exhibit a Newtonian plateau at low shear rates and show the shear thinning behavior at high shear rates. Lower viscosity of LCP in comparison to that of PP favors the elongation of LCP domains in a flow direction when blended with the PP matrix. This tendency has been supported by the results of mechanical tests performed for the samples cut out in the direction of extrusion as compared to those in the transverse direction, thus suggesting that a slight orienta-

tion of LCP was developed under processing. Because the Young modulus was not significantly modified, the orientation degree was expected to be not very high.

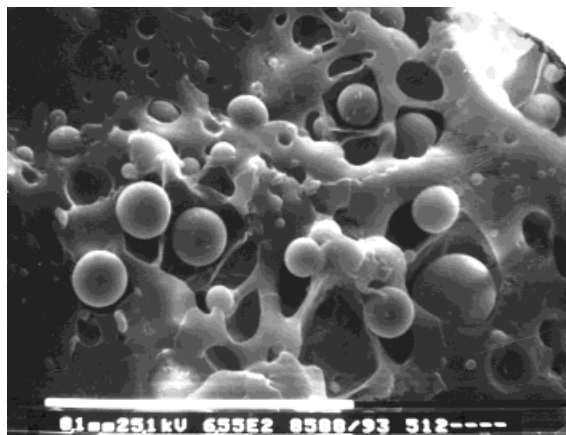
Morphology and Interfacial Tension

The above supposition has been verified by the scanning electron microscope (SEM) observations (Figs. 5 and 6). PP2-LCP2 80 : 20 blends, when extruded with a low shear rate (ca. 20 s⁻¹), exhibit the droplet morphology with a broad sphere-diameter distribution in a range of 1–30 μm [Fig. 5(a)]. The LCP spheres were easily separated from the matrix, which has been deduced from the distinct indentations of the removed spheres, without ductile fibrillation at interfaces.

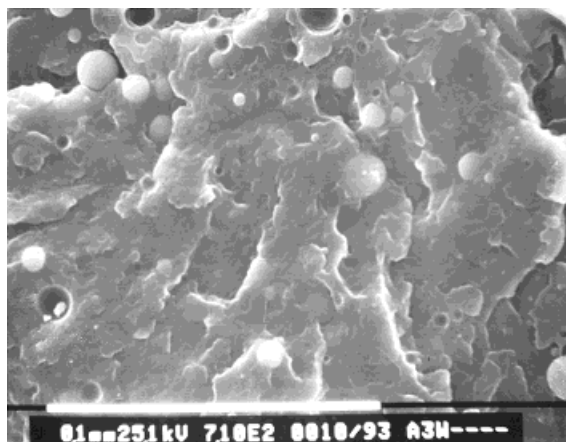
Compatibilization with PP-*g*-MAH brings



(a)



(b)



(c)

Figure 5 Micrographs of PP2-LCP2 80 : 20 blends and alloys extruded at 20 s^{-1} : (a) blend; (b) alloy; (c) alloy with adhesion promotor.

about progressive unification of the droplets' diameter ($5\text{--}20 \mu\text{m}$), but the interfacial adhesion does not seem to be improved [Fig. 5(b)]. Better

adhesion has been revealed for the compatibilized blends, which additionally contain the adhesion promotor. LCP domains, although still in a droplet form of ca. $8 \mu\text{m}$ diameter, were embedded in a matrix, with the PP layer coating particular spheres [Fig. 5(c)]. That alloy exhibited the highest tensile modulus, which confirms our observation on enhancement in the interfacial adhesion between PP and LCP.

Extrusion of the blends with higher shear rate (ca. 2000 s^{-1}) induced some orientation in LCP domains. In the PP2-LCP2 80 : 20 blend, slightly elongated ellipsoids have been observed, which were removed easily from the matrix [Fig. 6(a)]. The diameter of LCP domains is in a range of $1\text{--}15 \mu\text{m}$.

Compatibilization gives rise to the improvement of interfacial adhesion, which has been confirmed by the observation that the LCP spheres were well wetted by the matrix and by a regular size distribution of the droplets, of which the average diameter is $3 \mu\text{m}$ [Fig. 6(b)]. High shear caused stretching of some LCP domains into fibers, but it has been rather an exceptional feature.

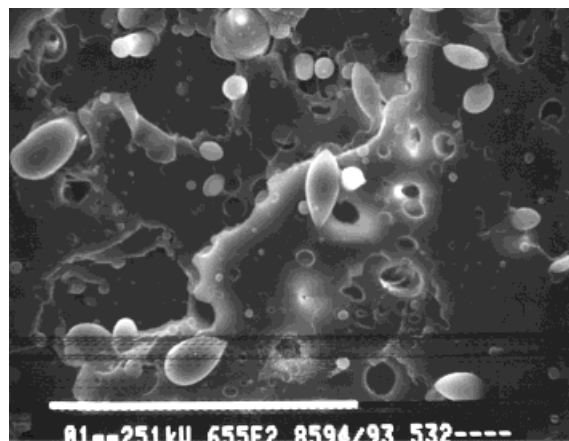
A very similar picture has been observed for the blend PP2-LCP2-PP-*g*-MAH-catalyzer, which exhibits regular LCP spheres of $3 \mu\text{m}$ diameter, small number of which is elongated into fibers [Fig. 6(c)].

Another explanation of the origin of the observed morphology according to La Mantia et al.⁸⁶ is that fibrils formed within the capillary were able to disappear if the relaxation time of the LCP is less than the average residence time in a capillary, or if the shear flow was so large that it caused breaking up of the fibrils into droplets. The morphology reported in Figure 6(b) and (c) suggests that both mechanisms are possible.

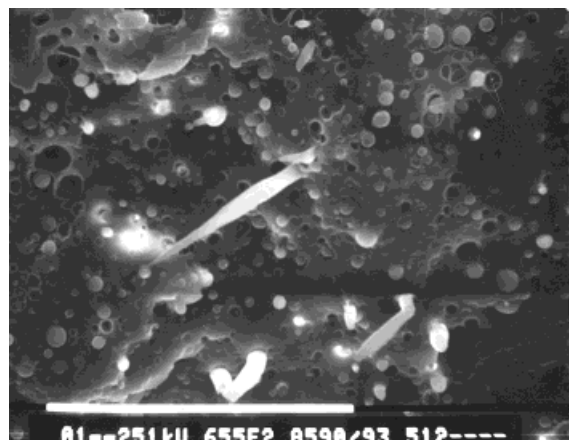
The above observations on the blend morphology can be related to the interfacial characteristics of heterogeneous systems, to which PP-LCP blends belong. LCP domains, while mixed in a molten state with PP, undergo breaking up into smaller domains under stress σ_{12} in a mixing device until the cohesive forces of surface tension counterbalance the viscous forces. The equilibrium condition can be written in the following form:

$$\sigma_{12} = \gamma_{12}/d \quad (1)$$

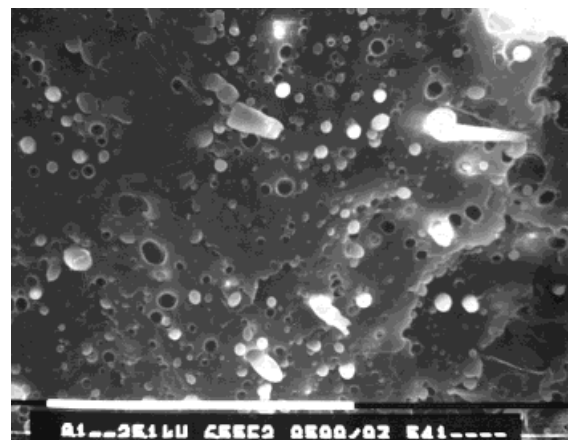
where γ_{12} is the interfacial tension and d is the



(a)



(b)



(c)

Figure 6 Micrographs of PP2-LCP2 80 : 20 blends and alloys extruded at 2000 s^{-1} : (a) blend; (b) alloy; (c) alloy with adhesion promotor.

droplet diameter. The ratio of the forces is called the Weber number (We), where

$$We = \sigma_{12}d/\gamma_{12} = \eta_m\dot{\gamma}d/\gamma_{12} \quad (2)$$

where η_m is the melt viscosity of the matrix and $\dot{\gamma}$ is the shear rate. According to Wu,⁸⁷ the critical condition for droplet breaking is

$$We_{cr} = 4\lambda^{\pm 0.84} \quad (3)$$

where λ is the viscosity ratio of the dispersed to matrix phase. When $\lambda > 1$, the exponent is positive, whereas it is negative for $\lambda < 1$.

In order to estimate the effect of a compatibilizer on the PP-LCP blends, we have performed an approximate evaluation of the interfacial tension. The approach of Good and Girifalco have been applied, which deals with interrelationship between the individual surface tension of two liquids γ_1 and γ_2 and their interfacial tension, as follows:

$$\gamma_{12} = \gamma_1 + \gamma_2 - 2\chi(\gamma_1\gamma_2)^{1/2} \quad (4)$$

The interaction parameter χ is often proposed to be close to unity, particularly if the cohesion forces of both phases have identical character to the adhesion forces in the phase boundary and if no polar interactions between the component exist, which is the case of PP-LCP system.

Using the data from literature^{41,50,88,89} and assuming that $d\gamma/dT = -0.056 \text{ mN m}^\circ\text{C}$, we have applied to the calculations $\gamma_{PP} = 14.3 \text{ mN m}$ and $\gamma_{LCP} = 32.0 \text{ mN m}$, thus obtaining $\gamma_{12} = 3.5 \text{ mN m}$. This value has been estimated according to $\gamma_{12} = \{14.3 + 32.0 - (14.3 \times 32.0)^{1/2}\} = 46.3 - 42.8 = 3.5 \text{ mN m}$.

A comparison of the droplet size in Figure 5(a) and (b) gives rise to the approximate evaluation of the compatibilizer efficiency, which gives reduction of the interfacial tension to $\gamma_{12} = 2.1 \text{ mN m}$. This value has been obtained if comparing the corresponding Weber number in Figure 5(a) and (b): $(\eta_m\dot{\gamma}d/\gamma_{12})^a = (\eta_m\dot{\gamma}d/\gamma_{12})^b$. The expression for the interfacial tension the Figure 5(b) state is thus $(\gamma_{12})^b = (d^b/d^a)(\gamma_{12})^a = (15/25) 3.5 = 2.1 \text{ mN m}$.

Smaller LCP domains observed in Figure 6 suit the Wu theory well since, at higher shear rate, the viscosity ratio $\eta_{LCP} : \eta_{PP}$ becomes lower. Using the room temperature data, $\gamma_{PP} = 29.4 \text{ mN m}$ and $\gamma_{LCP} = 46.3 \text{ mN m}$, one obtains the interfacial tension at a room temperature of 2.0 mN m . Once the data is obtained, the work of adhesion W can be calculated according to

$$W = \gamma_1 + \gamma_2 - \gamma_{12} \quad (5)$$

Thus, the work of adhesion for PP-LCP blend amounts of 73.7 mN m (resulting from $W = 29.4 + 46.3 - 2.0 = 73.7 \text{ mN m}$). A similar procedure, which takes into account the diameter of LCP droplets as shown on Figure 5, gives rise to the work of adhesion of 75.0 mN m for the system PP-LCP-PP-*g*-MAH. Again, the calculation is $W = 29.4 + 46.3 - 0.7 = 75.0 \text{ mN m}$.

Thus, PP-*g*-MAH in PP-LCP blends causes the work of adhesion to increase. The addition of 4 wt % of compatibilizer resulted in a slight increase in the work of adhesion, which is in agreement with our results of tensile tests, which revealed only a moderate increase in the moduli and no improvements in tensile strength. Therefore, we conclude that the compatibilizing effect of PP-*g*-MAH can be attributed exclusively to polar interactions with LCP but not to chemical reactions between the components. A similar supposition was done by other scientists^{24,77} who believe that compatibilization in PP-LCP and PP-PET systems using PP grafted with reactive monomers results rather from the specific interactions than true covalent reactions.

CONCLUSIONS

Our experiments led us to the conclusion that reinforcement of PP with LCP can be performed with the following limitations:

- (1) a matrix polymer of high thermal stability has to be used;
- (2) the ratio of the polymer components has to be optimized;
- (3) a compatibilizer brings about uniformity in LCP domain size, but its amount has to be matched in order to receive high interfacial adhesion and efficient reinforcement;
- (4) effective adhesion precursors of catalytic efficiency for interfacial chemical reactions are welcomed; and
- (5) high elongational stress should be developed under processing in order to stretch the LCP domains into fibers.

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