

Electrical Behavior of High Impact Polystyrene/Liquid Crystalline Polymer Blends Containing Low Content of Carbon Black

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ABSTRACT: This article presents a study of the structure and electrical behavior of carbon black (CB) containing immiscible polymer blends. A series of electrically conductive blends of high impact polystyrene (HIPS), liquid crystalline polymer (LCP), and CB was compounded and followed by a capillary rheometer extrusion process or by injection molding. In these immiscible blends, HIPS serves as a low surface tension matrix and LCP as a polar dispersed phase. Shear and elongational flow result in blend morphology consisting of highly elongated and oriented LCP particles dispersed in the HIPS matrix. The enhancement of conductivity in these blends is due to the affinity of CB to LCP and the formation of cocontinuous phase morphology, giving rise to conductive networks. Blends of various compositions were prepared using various processing conditions, emphasizing the

relationship between morphology, rheology, and electrical properties. The presence of at least 20 wt % LCP and 2 phr CB under certain processing conditions (mixing sequence and temperature) is necessary to obtain stable resistivity, independent of the studied extrusion shear rate, and low resistivity values. In addition, the processing mode significantly affects the blends' structure and the resultant electrical properties. Hence, injection molding due to high shear rates, elongational flow, and fast cooling results in high structural and electrical anisotropy. © 2006 Wiley Periodicals, Inc. *J Appl Polym Sci* 102: 1688–1696, 2006

Key words: liquid crystalline polymer (LCP); thermoplastic blends; carbon black; rheology; electrical conductivity; morphology

INTRODUCTION

Carbon black (CB) loaded immiscible polymer blends tend to exhibit a higher conductivity level than either polymer components at the same CB content. This phenomenon is due to the preferential CB location within one of the phases and the cocontinuous phase structure of immiscible blends at certain compositions. This pertains to a double percolation concept, i.e., continuity of the minor polymer component and continuous networks of the CB particles within or upon that phase.^{1,2} The preferred location of fillers in an immiscible polymer blend is mainly due to the different affinity of filler particles to the blend's components. The delicate balance of polymer properties such as surface tension and viscosity, and processing conditions (thermodynamic and kinetic considerations) controls this affinity and thus the preferred localization.³

In blending of immiscible thermotropic liquid crystalline polymers (LCPs) with thermoplastic polymers under certain shear and elongational flow fields, the dispersed LCP droplets are deformed into ellipsoids

and fibrils. After quenching, the LCP fibrils maintain their structure, because of their long relaxation time. They reinforce the matrix owing to their inherent strength and stiffness.^{4–7} LCP at low concentrations is also known as a processing aid, since it can reduce the viscosity of blends, thus improving processability.⁸

Tchoudakov et al.^{2,9} studied the electrical properties of immiscible polymer blends containing high impact polystyrene (HIPS), LCP, and CB. The LCP phase morphology in the blends was found to be sensitive to the processing conditions. These authors reported that a blend composition of at least 20 wt % LCP and 2 phr CB is necessary to preserve the conductivity of extruded filaments produced over a wide range of shear rates. LCP phase elongation and transformation from particles into sheet-like structures were accompanied by restructuring of the initially formed CB clusters into an ordered CB network located upon the LCP particles surface. A good agreement of resistivity values of injection molded blends and resistivity of filaments produced under similar conditions by a capillary rheometer was obtained.

The present study addresses HIPS/LCP/CB blends containing low CB contents of various compositions and processing conditions, emphasizing the relationship of morphology, rheology, and electrical proper-

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ties. The studied blend system was selected to include a highly deformable LCP (at $T > T_m$) as the dispersed phase, potentially forming an oriented continuous structure, which is preserved upon cooling.¹⁰ In addition, the two polymers are of different levels of surface tension, LCP being of the higher surface tension,¹¹ thus of higher affinity for CB.

EXPERIMENTAL

The Polymers used are high impact polystyrene (HIPS), Styron A-tech 1200, MFI = 5 g/10 min (Dow Plastics) and a liquid crystalline polymer (LCP), Rodrun LC-3000 (Unitika Co., Tokyo, Japan). The LCP consists of 60 mol % hydrobenzoic acid and 40 mol % polyethylene terephthalate. It has a melting temperature of 205°C. Carbon black (CB), Ketjenblack EC-600 (Akzo-Nobel, Netherlands), having a bulk density of 100–120 kg/m³, BET surface area of 1400 m²/g, and electrical volume resistivity of 10⁻² to 10¹ ohm cm, was used as the conductive filler.

Blends were prepared by a standard procedure of melt mixing a dry blended CB and the polymer components in a Thermo Haake Rheomix equipped with a 50 cm³ cell. The mixture was compounded at 210°C for approximately 15 min at 50 rpm. The resulting blends were then compression molded at 210°C. The volume resistivity was measured using the “two-parallel electrodes” method (DIN-53596). In this method, a known voltage is supplied and the electrical current passing across the sample thickness is measured. A voltage of 1 V was applied by a 240 A high-voltage supply, Keithley instruments, and the current was measured with a Keithley Electrometer 6514.

The binary blend composition is given in weight percentage, e.g., wt % polymer1/wt % polymer 2. The CB content is given in phr, i.e., parts CB per 100 g HIPS/LCP blend.

An alternative processing method used for selected formulations was compounding in a twin-screw extruder (Berstorff intermeshing twin-screw extruder, $L/D = 40$, $D = 25$ mm, operating in the corotating mode) at 210°C followed by injection molding (Battenfeld, $D = 35$ mm) at 210, 230, or 250°C and mold temperature of 50°C.

Extruded filaments were produced using a Rosand RH7 Capillary Rheometer (Bohlin Instruments) equipped with a capillary 20 mm long and 1 mm in diameter ($L/D = 20$), at 210 or 250°C. The blends were extruded at various plunger crosshead speeds, ranging from 0.1 to 100 mm/min, corresponding to a shear rate range of 3–3000 s⁻¹. The filaments were collected and used for electrical conductivity measurements, applying silver paint to minimize contact resistance and using a Keithley Electrometer 6514 instrument. Resistivity values above 10⁸ ohm cm are beyond the limit of the measuring device.

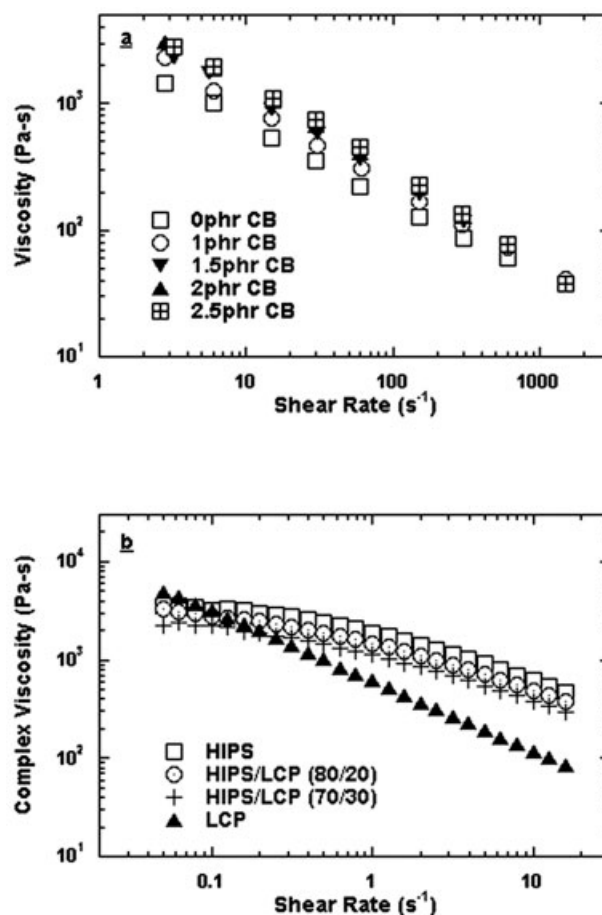


Figure 1 Viscosity versus shear rate of neat HIPS and LCP, and HIPS/LCP blends containing 20 and 30 wt % LCP: (a) 210°C, capillary rheometer; (b) 230°C, parallel plate rheometer.

The blends' morphology was studied using a Philips XL 20, scanning electron microscope (SEM). Surfaces observed were either brittle fracture surfaces, produced after quenching in liquid nitrogen, or LCP particles, obtained by removing the polystyrene matrix by extraction in toluene. All samples were gold sputtered prior to observation.

Rheological studies were conducted using a Rosand RH7 Capillary Rheometer and a Rheometric ARES Rheometer, equipped with a parallel-plate configuration using 25 mm diameter plates. Complex viscosity was measured in the oscillatory shear mode within the shear rate range of 0.05–15 s⁻¹. Flow reversal experiments, using the parallel plate rheometer, were carried out as described later.

RESULTS AND DISCUSSION

HIPS/LCP blends

Melt flow properties of the HIPS/LCP blends (without CB) are given in Figure 1(a) as the melt viscosity measured by the capillary rheometer, versus shear

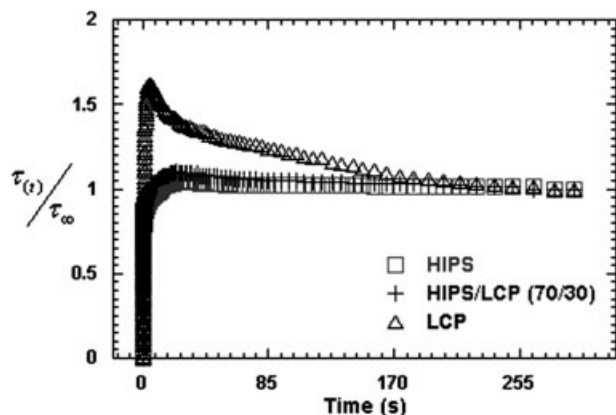


Figure 2 Normalized stress as a function of time in the reverse flow experiment for LCP, HIPS, and the 70HIPS/30LCP blend, 230°C.

rate, of the neat polymers, HIPS and LCP, and their blends containing 20 and 30 wt % LCP, at 210°C. The neat polymers and their blends exhibit a shear-thinning behavior, where HIPS has a higher viscosity than LCP throughout the entire shear rate range studied. The viscosity of the blends exhibits intermediate values, approaching at high shear rates the HIPS viscosity. Figure 1(b) presents the complex viscosity values, as measured by the parallel plate rheometer, versus shear rate (of neat HIPS and LCP) and their blends containing 20 and 30 wt % LCP at 230°C (measurements at 210°C could not be performed because of the parallel plate rheometer limits). A Newtonian behavior of HIPS and HIPS/LCP blends at the lower shear rate level is observed. Neat LCP exhibits pseudoplastic behavior, strongly shear rate dependant, in agreement with literature.^{4,12–14} The blends' complex viscosity exhibits slightly lower values than the neat components, in the lower levels of shear, while at higher rates their viscosity values lie in between the two neat components, closer to HIPS.

It has been suggested that the formation during flow of elongated fiber such as LCP droplets results in lubrication of the thermoplastic matrix.^{12,13} The lower viscosity of the LCP than that of the matrix coupled with the lubrication effect results in intermediate blends viscosity values. Polycarbonate/LCP blends were reported to exhibit viscosity values lower than those of both components.¹⁵

Figure 2 depicts flow reversal experimental^{16,17} results, conducted to study the relaxation behavior, using the parallel plate rheometer. The following deformation history was applied to the sample: First, the sample was sheared for 300 s at 0.1 s⁻¹; the flow was stopped, and the sample was kept quiescently for a predetermined time (rest time) of 600 s. Finally, the sample experienced shearing in the reverse direction for 300 s at 0.1 s⁻¹. The shear stress was monitored during the last period. The

stress response presented as the stress as a function of time (τ_t) normalized by the stress at time infinity (τ_∞) displays a significant overshoot for the neat LCP, a slight overshoot for the 70HIPS/30LCP blend, and zero overshoot for the neat HIPS. Thus, the overshoot phenomenon is attributed to the long relaxation behavior of the LCP phase. During the first shearing stage of LCP, the stiff molecules organize into oriented domain structures. Then even for a prolonged period of rest, after shearing is stopped and the stress causing deformation is removed, the persistence of order in the material is kept. When shearing is applied in the reverse direction, the polydomain structure of LCPs exhibits high initial resistance to flow. To overcome the ordered structure, a certain stress level must be initially exceeded, depicted as a stress overshoot. Once the material starts to flow, progressive shear thinning prevails.^{10,18,19} The 70HIPS/30LCP blend undergoes only a slight stress level overshoot before starting to flow. This slight overshoot stems from the LCP phase dispersed within the HIPS matrix, which by itself has shown no stress overshoot.

HIPS/LCP blends exhibit a two-phase morphology, where in the studied composition range, the minor LCP component is dispersed in the HIPS matrix. The LCP phase morphology strongly depends on the flow conditions. Figure 3 exhibits SEM micrographs of 70HIPS/30LCP filaments extruded at 210°C, at various shear rates, fractured perpendicular to the flow direction. The most dominant feature seen is the finer dispersion of the LCP particles as shear rate increases; the LCP particles' diameter decreases from about 30 μm at low shear rates to about 5 μm at the higher shear rates.

Two main driving forces acting upon the surface of a deforming LCP droplet influence the size of LCP particles: shearing and elongational forces tending to deform the droplet and interfacial tension tending to resist these forces and keep the droplet large and spherical. The process of droplet deformation and breakup due to shearing forces continues as long as the droplets surface tension force is high to overcome the viscous shearing forces.²⁰ In addition, the level of droplets coalescence, largely determined by the dispersed phase content, affects the final droplets size.

Figure 4 compares changes in the skin morphology, parallel to the flow direction, at low and high shear rates for 70HIPS/30LCP filaments extruded at 210°C. At low shear rates [Fig. 4(a)], LCP morphology is fibrillar and nonuniform in diameter. This is related to inhomogeneous stretching in the flow direction. At high flow rates [Fig. 4(b)], both dense fibrous network, aligned in the flow direction, and sheet-like structure appear. The fibrils are almost uniform in their diameter.

HIPS/LCP/CB blends

The electrical resistivity of a CB-filled polymer as function of CB content is characterized by a percola-

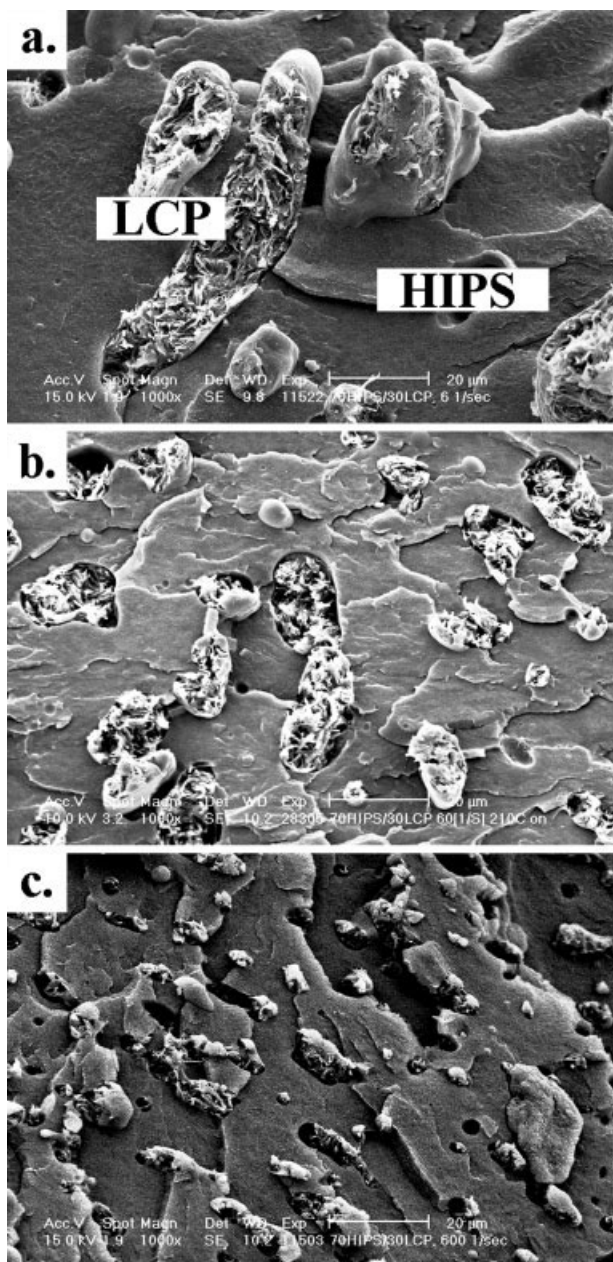


Figure 3 SEM micrographs of 70HIPS/30LCP filaments produced at 210°C and at different shear rates: (a) 6 s⁻¹; (b) 60 s⁻¹; (c) 600 s⁻¹, freeze fractured perpendicular to the flow direction.

tion behavior, where at the percolation threshold the resistivity sharply decreases by several orders of magnitude. Figure 5 depicts resistivity curves of HIPS/CB, LCP/CB, and HIPS/LCP/CB compression molded blends, compounded and molded at 210°C.

These typical percolation curves display HIPS/CB and LCP/CB percolation thresholds at 2 and 3.5 phr CB, respectively. This difference in percolation threshold is attributed to the different values of surface tension and viscosity of the two polymers.^{11,21} The interfacial energy plays an important role in the con-

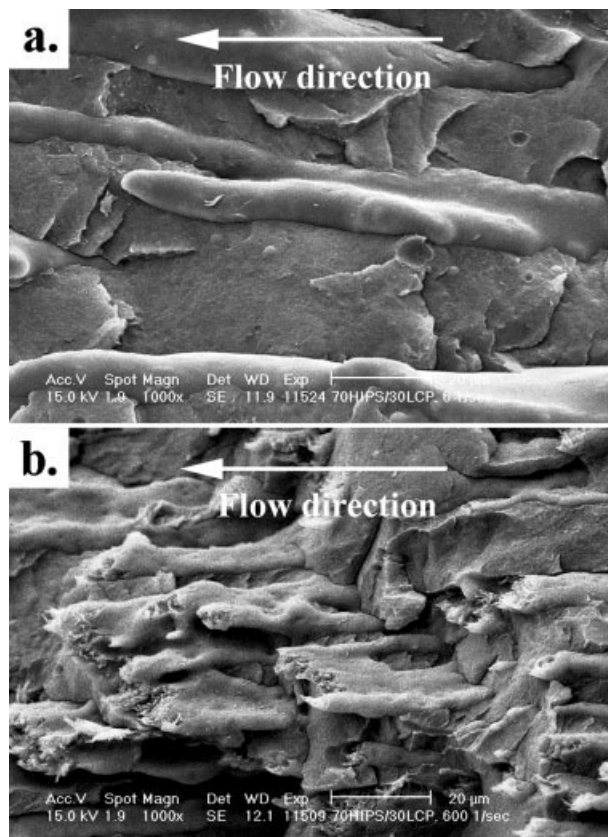


Figure 4 SEM micrographs of 70HIPS/30LCP filaments produced at 210°C and at different shear rates: (a) 6 s⁻¹; (b) 600 s⁻¹, freeze fractured parallel to the flow direction.

ductive path formation in the CB loaded polymer; the higher the surface tension, the higher is the percolation threshold. In systems having a high matrix/CB interfacial energy, e.g., HIPS/CB, the formation of a CB/CB interface is energetically favored, leading to the formation of a conductive network at low CB content. Whereas, in a system that readily wets the CB,

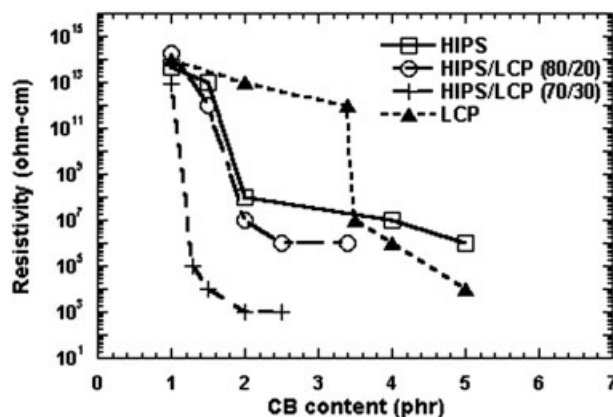


Figure 5 Resistivity versus CB content of compression molded neat polymers and HIPS/LCP blends containing 20 and 30 wt % LCP, compounded and molded at 210°C.

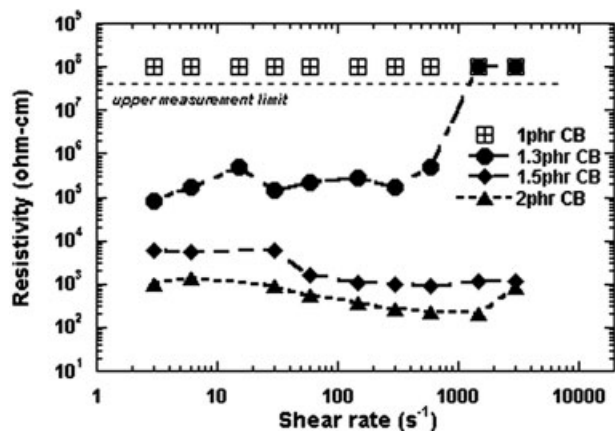


Figure 6 Resistivity versus extrusion shear rate of 70HIPS/30LCP/CB filaments at different CB contents, extruded at 210°C.

e.g., LCP/CB, the same particles at the same level of loading are more uniformly dispersed, hence, higher CB contents are needed for percolation.²² The HIPS has a higher viscosity than the LCP, thus decreasing the percolation threshold by increasing the level of CB agglomerates breakage.

The resistivity curves of the CB-loaded immiscible blends exhibit a decrease in the percolation thresholds relative to the CB-loaded neat polymers. The 80HIPS/20LCP blend percolates at approximately 2 phr CB, slightly less than the HIPS/CB percolation threshold. However, the 70HIPS/30LCP blend percolates at approximately 1 phr CB, significantly lower than the individual polymers percolation threshold; this is due to the previously described double percolation principle.

According to the double percolation principle, the CB is preferentially located upon the surface and within the minor continuous LCP phase; thus, the effective CB content is much higher than the nominal content. The preferred location of CB upon and in the LCP phase is attributed to the high polarity and low viscosity of the LCP when compared with HIPS.^{1,23}

The 70HIPS/30LCP/CB filaments (Fig. 6) exhibit the uniqueness of double percolation; the phase containing the CB forms a continuous structure, i.e., continuity of the minor polymer component where CB is located. As depicted in Figure 6, the 70HIPS/30LCP/CB filaments exhibit too high resistivity levels beyond the measuring limit of the instrument at 1 phr CB. However, at a slightly higher CB content of 1.3 phr, the filaments exhibit almost a stable electrical behavior, up to about 1000 s⁻¹, thus below 1000 s⁻¹, the system is beyond the percolation threshold. Addition of CB, beyond 1.3 phr, further decreases the resistivity and preserves the resistivity level throughout the studied extrusion shear rate range. The resistivity values of the filaments prepared at low shear rates are similar to the values of the corresponding compression moldings.

The addition of CB to immiscible polymer blends alters the morphological structure. The morphology alteration depends on the initial blend structure. The 70HIPS/30LCP blend, consisting of spherical LCP particles dispersed in the HIPS matrix [Fig. 7(a)], exhibits a change in the particle size; upon the CB addition [Fig. 7(b)], the dispersed LCP particles become smaller. The reduction in the dispersed particle's size has been previously reported^{22,24,25} and has been attributed to the higher viscosity of the dispersed droplets upon CB addition. The CB particles located upon the LCP droplet's surface may also hinder droplets coalescence.

Figure 8 exhibits SEM micrographs of 70HIPS/30LCP and 70PP/30LCP/1.5CB filaments, freeze fractured parallel to the flow direction, clearly showing the continuous network structure. Figure 8(a) depicts the LCP phase forming an oriented fibrillar structure within the HIPS matrix. Figure 8(b) displays the preferred location of the CB, upon the surface of the continuous LCP fibrils, thus continuous networks of the CB particles. Anisotropy in structure should lead to anisotropy in electrical properties.

Figure 9 displays SEM micrographs of 70HIPS/30LCP and 70HIPS/30LCP/CB filaments, produced at

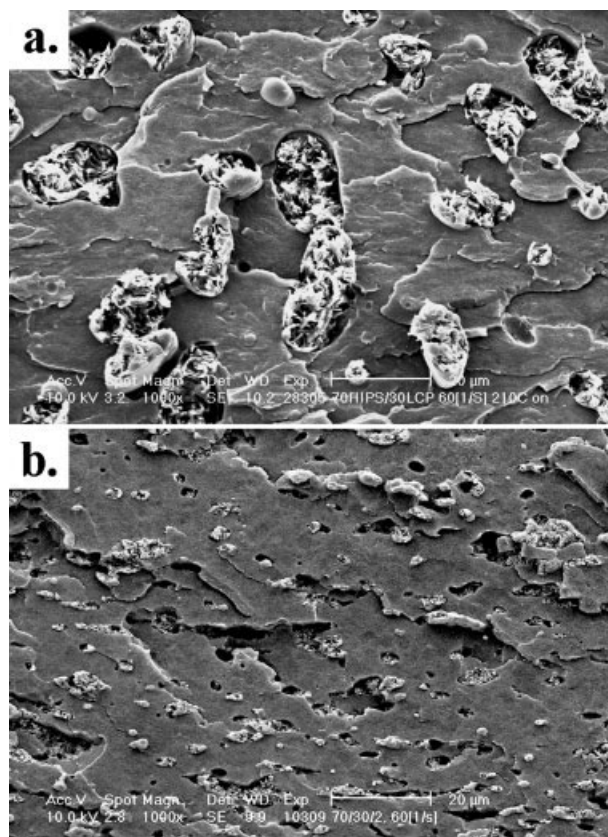


Figure 7 SEM micrographs of (a) 70HIPS/30LCP and (b) 70HIPS/30LCP/2CB filaments produced at 210°C and 60 s⁻¹, freeze fractured perpendicular to the flow direction.

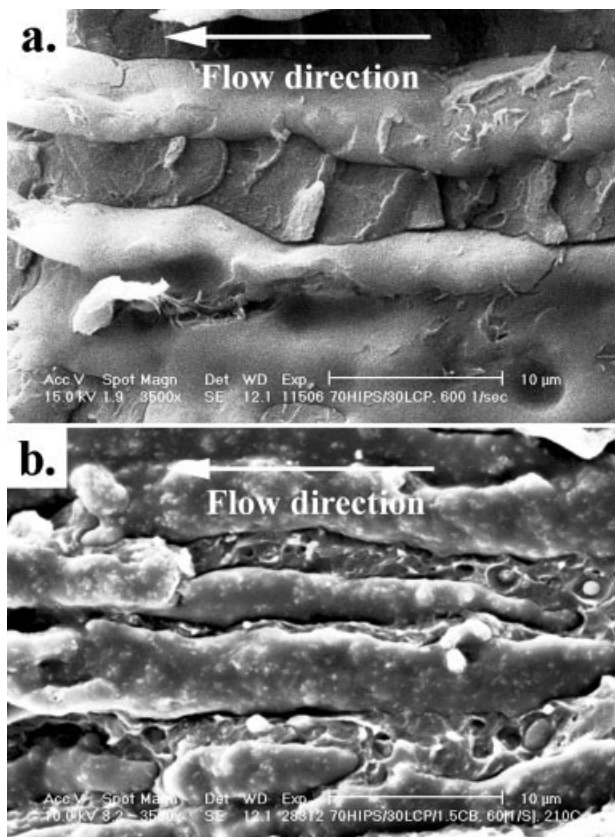


Figure 8 SEM micrographs of (a) 70HIPS/30LCP and (b) 70HIPS/30LCP/1.5CB filaments produced at 210°C and 60 s^{-1} , freeze fractured parallel to the flow direction.

various shear rates, after extraction of the HIPS matrix in toluene hence, the LCP particles. In general, as shear rate increases, the LCP particles exhibit a more elongated and thinner structure, due to the higher deformation during flow. Figure 9(a) shows large and nonuniform LCP particles produced at a low shear rate. At intermediate shear rates [Fig. 9(b)], the LCP particles become more elongated and uniform fibrillar structure. A partially sheet-like structure is formed at the high shear rates [Fig. 9(c)]. The addition of CB increases the viscosity of the dispersed droplets, leading to reduction of particle size.²⁶ In addition, CB located upon the LCP droplet surface affects its characteristics. Indeed, comparison of extracted filaments with and without CB [Figs. 9(a) and 9(d)], especially at the low shear rate, demonstrates this pronounced reduction. Moreover, the structure, as depicted for the CB loaded filaments [Figs. 9(d)–9(f)], is highly affected by the level of shear rate, exhibiting variation from particles to elongated fibrils to a sheet-like structure.

The 70HIPS/30LCP system exhibits, above percolation threshold, a stable electrical behavior, throughout the whole extrusion shear rate applied (Fig. 6), different from the electrical behavior of the 20 wt % LCP containing blends (Fig. 10). In Figure 10 at 1 phr CB,

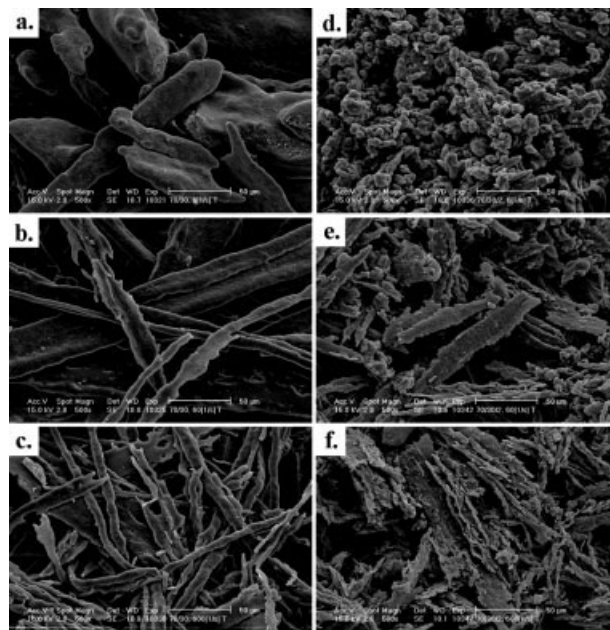


Figure 9 SEM micrographs of 70HIPS/30LCP filaments produced at 210°C and at different shear rates: (a) 6 s^{-1} ; (b) 60 s^{-1} ; (c) 600 s^{-1} ; and 70HIPS/30LCP/2CB filaments produced at 210°C and at different shear rates: (d) 6 s^{-1} ; (e) 60 s^{-1} ; (f) 600 s^{-1} , after HIPS extraction in toluene.

the system exhibits high resistivity values throughout the studied extrusion shear rate range (beyond the measuring capacity of the instrument). The other three systems containing 1.5, 2, and 2.5 phr CB exhibit systems where the resistivity abruptly changes along the studied extrusion shear rate range. At the low shear rate, the 20 wt % LCP systems exhibit high resistivity values (actually insulating materials). This is attributed to the discretely dispersed spherical LCP particles in these blends, incapable of forming a continuous network. On the contrary, at the intermediate and high shear rate levels, low resistivity values are exhib-

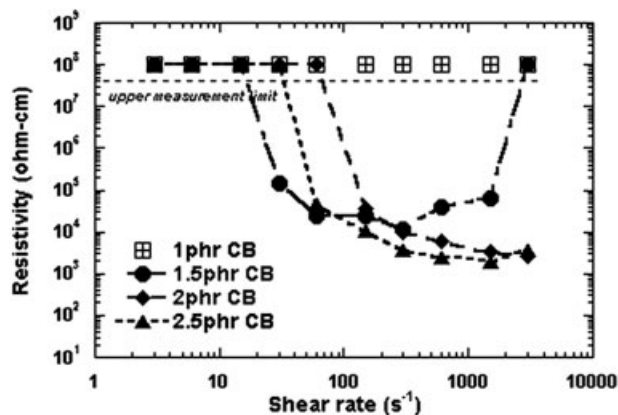


Figure 10 Resistivity versus extrusion shear rate of 80HIPS/20LCP/CB filaments for different CB contents, extruded at 210°C.

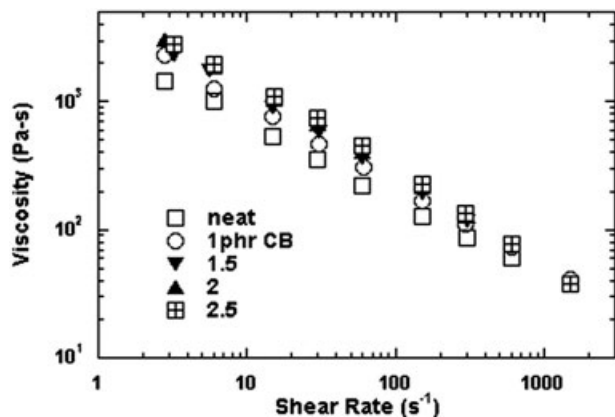


Figure 11 Melt viscosity versus shear rate of 80HIPS/20LCP/CB blends for different CB contents, extruded at 210°C.

ited. Under these conditions, the LCP particles are elongated and even forming sheet-like structures, transforming the 20 wt % LCP blends' structure into a cocontinuous one. This result emphasizes the importance of the combined effect of LCP content, CB content, and processing conditions on the formation of continuous phases leading to the desired LCP and CB continuities.

Figure 11 displays viscosity data for the 80HIPS/20LCP blends, neat and containing 1, 1.5, 2, and 2.5 phr CB, depicting a rise in viscosity with CB content at the low and intermediate levels of shear rate. At the higher level of shear rate, the viscosity values at all CB contents converge to similar values. The viscosity increase may result from the lower deformability of the CB containing LCP phase, and since the CB, located upon the LCP droplets, raises the thermodynamic stability of the multiphase blend,³ consequently diminishing the mobility at the interface and coalescence.

Previous studies^{22,24} have shown that the mixing sequence may have a significant effect on the electrical behavior of blends. Figure 12 exhibits the effect of mixing sequence on the electrical behavior of the 80HIPS/20LCP/2CB blend prepared at various extrusion shear rates. The [(LCP + CB) + HIPS] (LCP was first compounded with CB and HIPS was then added) and the [(HIPS + LCP) + CB] (HIPS was first compounded with LCP and CB was then added) blends show very high resistivity values. Interestingly, the [HIPS + LCP + CB] (all components simultaneously blended) and [(HIPS + CB) + LCP] (HIPS was first compounded with CB and LCP was then added) blends show low resistivity values at high shear rates.

In the [(HIPS + CB) + LCP] blend, which has the lowest resistivity values, upon the addition of LCP to the molten HIPS/CB compound under the dynamic mixing, the CB particles migrate from HIPS to the LCP particle's surface, since CB has a much higher affinity

to LCP. When the three constituents are mixed together, i.e., simultaneous mixing, the electrical behavior exhibits a slightly higher resistivity values than for the [(HIPS + CB) + LCP] blend. This can be explained since upon the increasing temperature CB disperses first in the melted HIPS matrix, and then migrates from HIPS to the LCP particles surface. CB particles' location upon the LCP particles' surface is the more efficient structure forming continuous CB networks, when compared with the [(LCP + CB) + HIPS] blend where CB is located within (rather than upon the LCP particles).

As evident from the SEM micrographs (Fig. 13), the dimensions of the dispersed LCP particles are smaller, and their dispersion is more uniform for the [(HIPS + CB) + LCP] blend when compared with the other blends. This result verifies the preferred location of CB particles upon the minor LCP phase surface. The [(HIPS + LCP) + CB] and the [(LCP + CB) + HIPS] blends show rather large LCP particles. The SEM micrographs are in agreement with the electrical properties; the better-dispersed blend showed the lower resistivity values. It is important to note that CB in all studied blends was preferentially located upon the surface and within LCP particles; therefore, the LCP level of dispersion is the major factor affecting the electrical properties.

The 80HIPS/20LCP/2CB blend did not show a stable, shear independent electrical behavior throughout the studied shear rate range. To stabilize its electrical behavior, the effects of processing temperature and mixing order were studied. Figure 14 summarizes the combined effects of processing temperature and mixing sequence on the resistivity values versus extrusion shear rate. The temperature effect is actually a viscosity effect; thus, a lower viscosity enhances CB clustering and buildup of CB networks.² Moreover, the lower viscosity may enhance the CB particles' migration to the LCP phase surface.

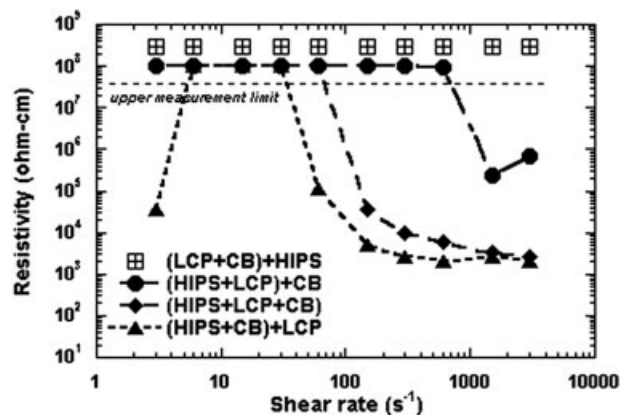


Figure 12 Resistivity versus extrusion shear rate of 80HIPS/20LCP/2CB filaments produced at different sequences of mixing, extruded at 210°C.

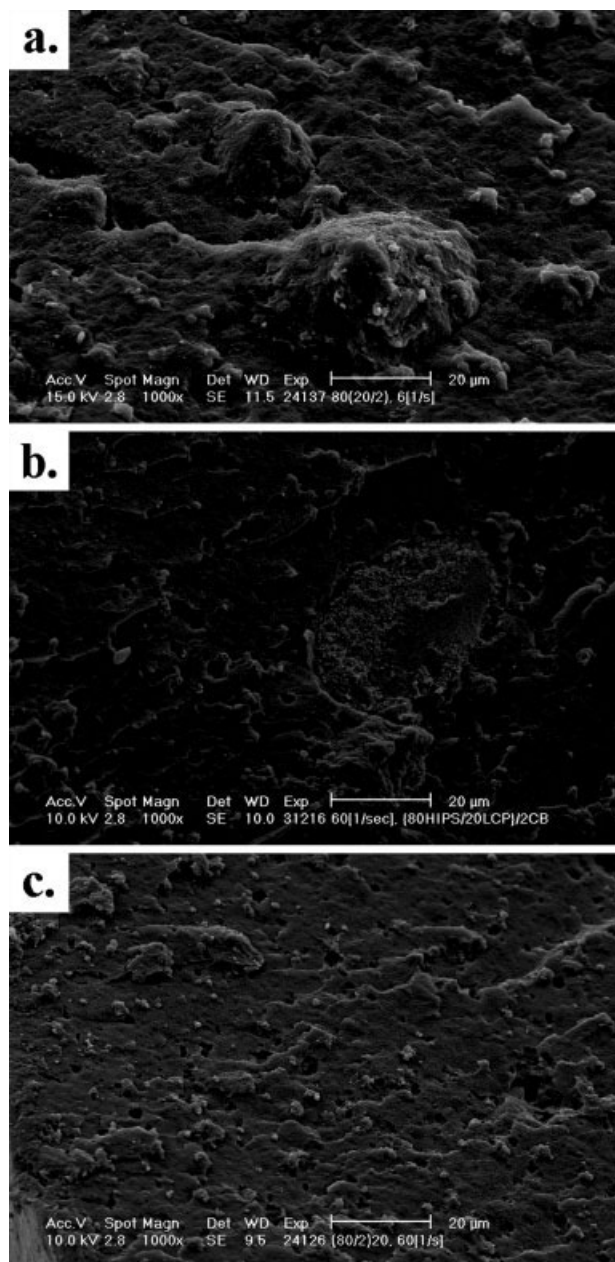


Figure 13 SEM micrographs of 80HIPS/20LCP/2CB blends: (a) [HIPS + (LCP + CB)]; (b) [(HIPS + LCP) + CB]; (c) [(HIPS + CB) + LCP] filaments produced at 210°C and 60 s⁻¹, freeze fractured perpendicular to the flow direction.

As expected, the higher processing temperature slightly improves the conductivity, but not throughout the whole shear rate range. The mixing sequence presenting the highest conductivity levels is again the [(HIPS + CB) + LCP] blend, which, at the higher processing temperature, becomes conductive throughout the entire shear rate range studied. Thus, a combination of mixing sequence and processing temperature causes the [(HIPS + CB) + LCP] blend to exhibit a double percolation behavior, independent of the filaments extrusion shear rate.

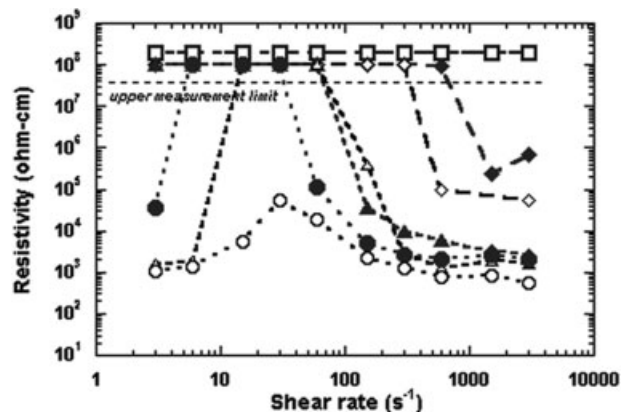


Figure 14 Resistivity versus extrusion shear rate of 80HIPS/20LCP/2CB filaments extruded at 210 and 250°C at different mixing sequences: (■) [(LCP + CB) + HIPS] 210°C; (□) [(LCP + CB) + HIPS] 250°C; (◆) [(HIPS + LCP) + CB], 210°C; (◇) [(HIPS + LCP) + CB], 250°C; (▲) [HIPS + LCP + CB], 210°C; (△) [HIPS + LCP + CB], 250°C; (●) [(HIPS + CB) + LCP], 210°C; and (○) [(HIPS + CB) + LCP], 250°C.

Injection molding

The resistivity and morphology of 70HIPS/30LCP/2CB injection molded samples were also studied. The electrical resistivity values measured parallel and perpendicular to the flow direction are summarized in Table I, for different injection molding temperatures. The electrical measurements parallel to the flow direction exhibit low resistivity values 10⁴ to 10⁵ ohm cm, while the electrical measurements perpendicular to the flow direction exhibit high resistivity values 10¹¹ to 10¹² ohm cm. These results apply to all studied temperatures; hence, the injection molded specimens exhibit as expected a clear anisotropy in their electrical behavior.

SEM observation of the HIPS/LCP/CB blend supports the structure anisotropy. Figure 15 exhibits a cocontinuous structure along the parallel to the flow direction. The dispersed LCP particles become highly extended in the flow direction, displaying a fibrillar structure of relatively low diameter (~1 μm) and wide distribution of lengths of the order of tens of micrometer. The morphological observations provide sup-

TABLE I
Resistivity of 70HIPS/30LCP/2CB Injection Molded Specimens as a Function of Temperature and Measurement Direction

Temperature	Flow direction	Resistivity (ohm cm)
210°C	Perpendicular	3.9E+12
	Parallel	2.7E+04
230°C	Perpendicular	8.5E+11
	Parallel	1.6E+05
250°C	Perpendicular	7.1E+11
	Parallel	1.7E+05

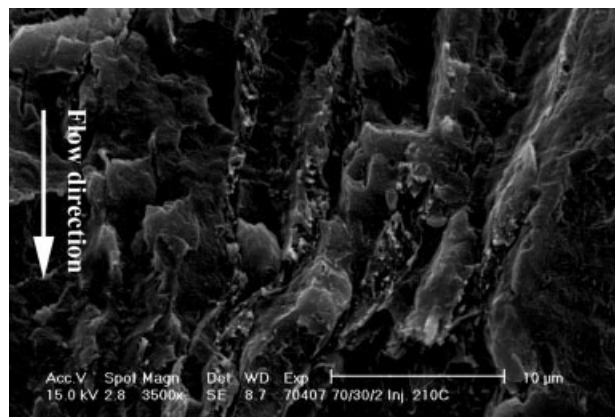


Figure 15 SEM micrographs of a 70HIPS/30LCP/2CB injection molded sample at 210°C, freeze fractured parallel to the flow direction.

port for the insulating behavior of the injection molded specimens in the perpendicular to flow direction. The high orientation of the minor LCP phase and CB located upon the phase surface results in an ordered sequence of elongated structures separated by the insulating HIPS matrix; the elongated conducting LCP particles hardly contact each other in the perpendicular direction and are separated by HIPS layers.

Injection molding, associated with high shear rate production level, orientation, and fast cooling, induces high level of electrical resistivity anisotropy through the formation of structure anisotropy. Similar results for other polymer blends have been previously reported.^{2,20,25} The structure anisotropy is similar to that in the high shear level filaments.

In summary, this article shows that the HIPS/LCP/CB systems are unique and efficient at low CB concentrations for the development of conductive extrusion and injection molding grades. Nevertheless, extruded and injection molded articles are expected to show electrical anisotropy.

CONCLUSIONS

Blends of HIPS/LCP containing CB were prepared and studied under different melt flow conditions, focusing on composition, resistivity, rheology, and morphology relationships. The presence of at least 20 wt % of LCP and 2 phr CB under certain conditions (mixing sequence and temperature) is necessary to obtain stable resistivity independent of the studied extrusion shear rate, and low resistivity values. This behavior of the (80HIPS/20LCP)2CB blend is due to its unique phase morphology, namely, highly oriented fibrillar and continuous LCP phase with fine CB particles preferentially located on the surface of the LCP phase,

forming a double percolating system. This structure formed during melt processing is maintained upon cooling due to the LCP long relaxation times, as shown by the rheological study. Mixing sequences affect both, the distribution of the LCP phase within the HIPS matrix and the CB within or upon the LCP particles, resulting in different structures and electrical properties. In addition, the processing mode significantly affects the structure and the resultant electrical properties. Therefore, injection molding, due to high shear level, elongational flow, and fast cooling, results in high structural and electrical resistivity anisotropy.

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