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# FILM PROCESSABILITY, MORPHOLOGY, AND PROPERTIES OF POLYAMIDE-6/LOW DENSITY POLYETHYLENE BLENDS

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**ABSTRACT:** The processing, morphology, and tensile properties of blown films prepared from polyamide-6 (PA6) and low density polyethylene (LDPE) blends with and without compatibilizer (Surlyn<sup>®</sup> 9020) are studied. The results indicate that the presence of PA6 and a compatibilizer has a great influence on blend rheology as well as mechanical and barrier properties of LDPE films where the morphology of the dispersed phase (PA6) plays an important role. In this study, film morphology is controlled mainly by variations in draw ratio and bubble pressure. It is shown that biaxial orientation of the films explains the anisotropic behavior of the mechanical properties and improved barrier properties due to the production of a lamellar structure.

**KEY WORDS:** blends, film, anisotropy, lamellar structure.

## INTRODUCTION

**P**RODUCTION OF POLYMER films is of great importance from a commercial point of view, especially in packaging [1]. It is common to co-extrude multilayer films composed of distinct layers acting as barriers, mechanical properties enhancers, etc. An alternative method to improve film properties is to directly use blends of commercial polymers.

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These blends are generally easier to process, require lower investments, and do not need developing new molecules for each specific application. The final film properties made from blends depend on the individual component properties, morphology, interphase, composition, and processing method [2]. Since blends of immiscible or partially miscible polymers are heterogeneous materials, the method and intensity of mixing influence the blend morphology which in turn affects the resulting physical properties of the film. Furthermore, rheological properties like shear and elongational viscosities under real processing conditions are important parameters controlling blend morphology. The relationships between all these parameters have been studied for several systems [2–6]. For example, Yeh et al. [5] reported that the melt shear viscosity of high density polyethylene (HDPE) is highly influenced by the content of polyamide (PA6) which in turn influences the production film blends by blow-molding.

Recently, reports on the barrier properties and deformation of PA6 drops in HDPE, with and without compatibilizer (Surlyn<sup>®</sup> 9020), have been made in the case of ribbon extrusion [6]. This processing method is known to induce uniaxial orientation which improves the physical properties in the machine direction (MD). Unfortunately, properties in the transverse direction (TD) are usually low [7,8]. In contrast, biaxial orientation is known to increase properties in both directions [9,10].

In film blowing, the polymer is biaxially oriented in the melt state and rapidly cools down in order to freeze the oriented structure [9]. Several studies [7–10] focused on the structure of polyethylene blown films, especially orientation and anisotropy of polyethylenes. The main parameter controlling anisotropy, for example MD/TD tear resistance, is the lamellar structure of the film (morphology). Molecular orientation imparted during film blowing is known to have a major effect on the mechanical properties. Therefore, characterization of film morphology is crucial to predict the final properties of the films, especially for polymer blends.

Compatibilization of polyolefin blends using condensation polymers has been studied extensively in the last decades not only for scientific, but also for industrial applications [11–15]. In particular the system PA6/HDPE has been produced by ribbon extrusion [6], blow-molding [5,13,15], and compression molding [12,16,17]. Other systems like PA6/polyethylene terephthalate (PET) [18], low density polyethylene LDPE/ethyl-vinyl alcohol (EVOH) [19], and PA6/EVOH [20] received a lot of attention due to their application in packaging. Films of compatibilized LDPE/PA6 did not receive as much attention except for

the work of La Mantia et al. [21] who reported that the film blowing operation could not be processed without compatibilization.

The main objective of this work was to study the morphology, tensile properties, and permeability of LDPE/PA6 blown films with and without compatibilization. Tensile modulus in both MD and TD are reported and the results are related with the morphology of the film as controlled by the biaxial deformation of the blend in the blowing process. A focus is made on the effects of PA6 content, draw ratio, and stretching force.

## **EXPERIMENTAL DETAILS**

### **Materials**

Low density polyethylene (LDPE) PX20020 by PEMEX was used as the continuous phase, while polyamide-6 (PA6) 3100 by Celanese was used as the dispersed phase. Surlyn<sup>®</sup> 9020 by DuPont was added as an interfacial agent. This ionomer is a random terpolymer consisting of 80% polyethylene with 20% composed of a mixture of methacrylic acid and isobutyl acrylate. The methacrylic acid is partially neutralized with zinc (70%). It has been demonstrated that this ionomer is an excellent compatibilizer for PA/PE systems because covalent bonding takes place between the carbonyl group of the ionomer and the terminal amine of the polyamide [11]. In this study, blends of 10, 20, and 30% PA6 in LDPE with and without compatibilizer were produced.

### **Preparation of Blends**

Prior to mixing, PA6 was dried under vacuum for 24 h at 80°C to eliminate excess moisture. Blends were prepared in an intermeshing co-rotating twin-screw extruder (Leistritz Micro 27 GL/GG-36D) with and without compatibilizer. Feeding was done under an inert dry nitrogen atmosphere and the decompression zone of the extruder was under vacuum. Cooling of the extrudate at the die exit was performed in water at room temperature. Typical temperature settings along the extruder barrel were 170/180/190/200/210/225/235/250°C from feed to die. The melt temperature was measured at the die by a thermocouple in direct contact with the melt and maintained constant at 250°C, and the screw speed was set at 100 rpm. For compatibilized blends, a masterbatch of LDPE and 3 wt% of ionomer was first prepared. This masterbatch was then mixed with the minor phase (PA6). Willis et al. [11] observed a high affinity of Surlyn for PA6 and ionomer migration to

the interface is facilitated when it is initially mixed with the component having the least affinity (polypropylene in their case). After extrusion, the blends were pelletized.

### Rheological Analysis

The rheological characterization of the PA6 and the blends were performed using a constant strain rate rheometer (ARES, TA Instruments). Parallel plates of 25 mm were used and the oscillatory measurements were performed under a flow of nitrogen. First, strain sweeps were performed to assure that the measurements were in the linear viscoelastic regime. For both polymers, strains between 3 and 5% were used for gaps between 1.25 and 1.7 mm.

### Preparation of Tubular Films

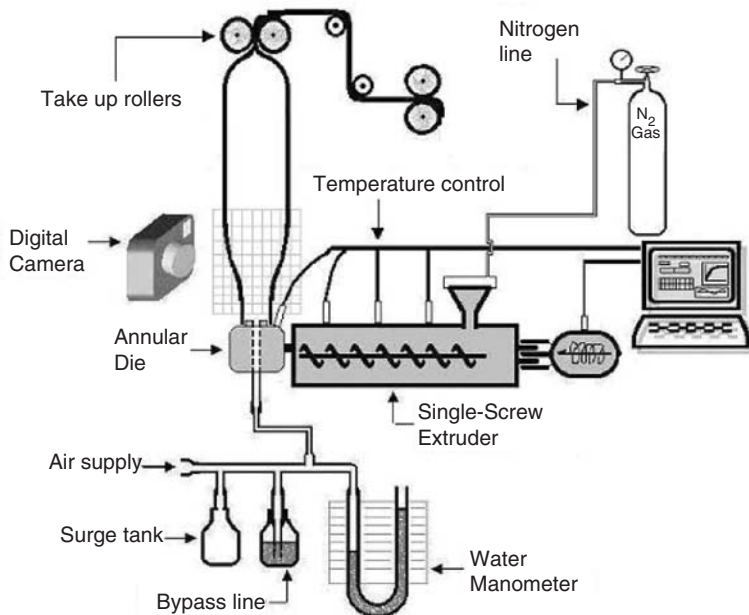
A single-screw extruder (Haake Rheomix 254) coupled with a blown-film device was used to prepare tubular films. Technical specifications of the experimental setup are reported in Table 1. In order to eliminate moisture, the blends were previously dried under vacuum for 24 h at 80°C and feeding was performed under a dry nitrogen atmosphere. This step was found to be important, because when no nitrogen was used, film production of uncompatibilized blends was unstable and the bubble could not be sustained. This is related to the hygroscopic nature of PA6 where the absorbed humidity has a tendency to form gas bubbles during processing. This may explain why La Mantia et al. [21] were not able to produce their

**Table 1. Specifications of the film blowing equipment used (single-screw extruder Haake Rheomix 254).**

<b>Barrel</b>	
Screw diameter, $D$	19 mm
Screw length, $L$	25 $D$
Heating zones	3
<b>Annular die</b>	
Diameter	25 mm
Pin diameter	24 mm
Gap width	0–0.8 mm
<b>Functionality</b>	
Heater capacity/zone	1000 W

film when no compatibilizer was added. For a compatibilized blend, as reported for the system PA6/polystyrene [22], blends containing compatibilizers absorb less water than uncompatibilized blends. This can be associated with the reaction produced between the compatibilizer and PA6 leading to size reduction of the micro-domain. This morphological change modifies barrier properties (water permeability) and water uptake [22].

Figure 1 shows a schematic of the system used. A water manometer was fixed with the blowing air feed to measure the bubble differential pressure and a bypass line was used to mitigate pressure variations inside the bubble. A digital camera and a squared pattern were used to measure the freeze-line height. The angular velocity of the take-up rollers and the final film diameter and thickness were also measured in order to calculate the polymer flow rate. Different draw ratios ( $DR = V_f/V_0$ ), defined as the take-up roller velocity ( $V_f$ ) divided by the extrusion velocity ( $V_0$ ), were used to study the effect of this parameter on morphology, barrier, and tensile properties. One important parameter in the film blowing process that is seldom reported is the stretching force ( $F$ ) [23–25]. Similar to earlier investigations [24,25],



**Figure 1.** Schematic diagram of the film blowing experimental set-up.

the stretching force was measured using a device based on the principles of a torque wrench and consisting of two rubber rolls. The processing conditions are given in Table 2 and further details of the equipment can be found elsewhere [25].

## Morphology

The films were first fractured in liquid nitrogen in both MD and TD. The samples were then coated with a gold-palladium alloy and micrographs taken using a scanning electron microscope (SEM), JOEL 5400 LV. Morphological analysis of the blends was performed at three positions: the exit of the twin-screw extruder (compounding), the exit of the single-screw extruder (blowing), and on the resulting films. The micrographs were finally analyzed with Image-Pro Express software (Media Cybernetics) where the dispersed particles were measured and quantified. At the exit of both extruders, the particles were found to be spherical and a statistical correction was applied to the diameter distribution according to the method of Saltikov [26].

## Tensile Tests

Tensile properties were determined at room temperature using a United machine (model Smart-1 SM10-20-30) in accordance with

**Table 2. Processing parameters for film blowing of LDPE/PA6 blends.**

Processing parameter	Nomenclature	Value	Units
Die radius <sup>a</sup>	$R_0$	12.15	mm
Die gap <sup>a</sup>	$H_0$	2.9	mm
Volumetric flow <sup>a</sup>	$Q$	10.86	cm <sup>3</sup> /min
Bubble pressure <sup>a</sup>	$P$	195.9	Pa
Draw ratio <sup>a</sup>	$DR = V_f / V_0$	12–112	–
Thickness ratio <sup>b</sup>	$TR = H_0 / H_f$	21–195	–
Blow-up ratio <sup>b</sup>	$BUR = R_f / R_0$	1.8–2.6	–
Freeze-line height <sup>b</sup>	$Z$	2.1–5.7	cm
Die temperature <sup>a</sup>	$T_d$	250	°C
Solid density of LDPE at 25°C <sup>c</sup>	$\rho_S$	0.92	g/cm <sup>3</sup>
Solid density of PA6 at 25°C <sup>c</sup>	$\rho_S$	1.13	g/cm <sup>3</sup>
Melt density of LDPE at 250°C <sup>c</sup>	$\rho_m$	0.73	g/cm <sup>3</sup>
Melt density of PA6 at 250°C <sup>c</sup>	$\rho_m$	0.96	g/cm <sup>3</sup>

<sup>a</sup>Fixed parameters in the experimental design.

<sup>b</sup>Measured parameters.

<sup>c</sup>[29].

ASTM D882-02 method. In order to study anisotropy, two sets of specimens were prepared having their longer axis parallel and normal to the suspected direction of anisotropy (TD and MD), respectively.

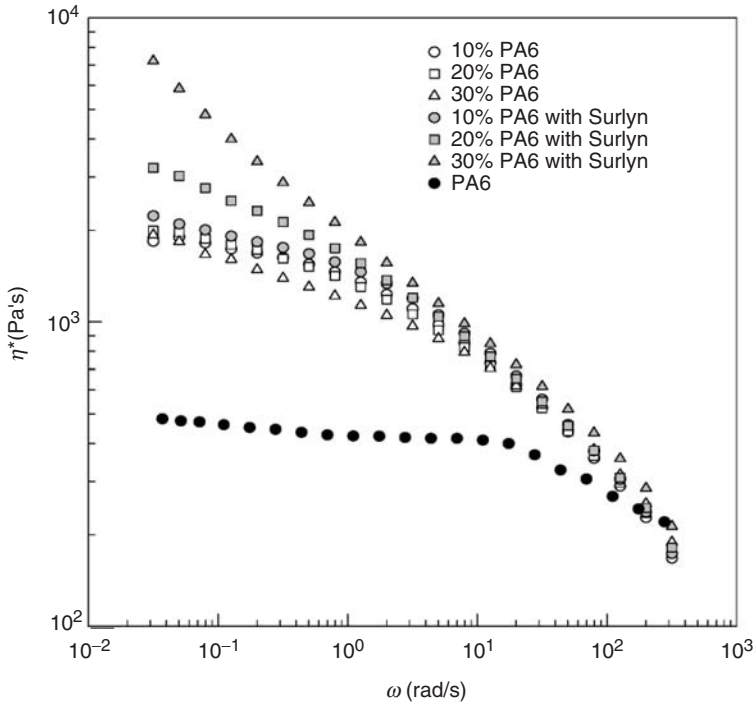
## **Barrier Properties**

An experimental method [6] based on a gravimetric permeation cell was used to measure the permeability of the films. The "Teflon" PTFE cell is basically a liquid container with the film used as a membrane seal on its top. The use of Teflon ensures that the liquid inside the cell does not react with the cell surfaces. The cell filled with the liquid (toluene) is inverted so that the liquid is in contact with the film. A concentration gradient across the polymeric membrane is thus established, and a decrease in the overall weight of the cell is measured. From the slope of a plot ( $M_0 - M_t$ ) versus time, where  $M_0$  is the initial weight and  $M_t$  is weight at any time, it is possible to calculate the permeability factor (expressed in mmol of toluene/s times the film thickness normalized by the area).

## **RESULTS AND DISCUSSION**

### **Rheology of Polymer Blends**

For the sake of clarity, Figure 2 shows only the complex viscosity of the PA6 and blends with and without compatibilizer while a complete rheological characterization of the PE was reported elsewhere [24]. In general, an increase in viscosity can be seen due to the presence of the compatibilizer. As previously described by Willis et al. [11], this behavior is related to the localization of the ionomer at the interface decreasing the interfacial mobility of the disperse phase. Chang and Hwu [27] showed that a higher viscosity of the compatibilized blends indicates better compatibility. Figure 2 also shows that viscosity of the blends without compatibilizer decreases with PA6 content due to increased coalescence; i.e., dispersed phase particle size increases as discussed later. Apparently, this macro-domain structure facilitates the flow of the blends in the melt state. Germain et al. [28] observed that for low shear rates, the viscosity of PP/PA6 blends is higher than the matrix viscosity, while the opposite occurs at high shear rates.



**Figure 2.** Complex viscosity as a function of frequency at 250°C for the blends and PA6.

**Film Processability**

Figure 3 shows the regions where it was possible to collect experimental data; i.e., stable bubble operation. Considering mass conservation, it is possible to calculate the mass flow ( $w$ ) as:

$$w = \pi[(R_0 + H_0)^2 - R_0^2]V_0\rho_m = 2\pi R_f H_f V_f \rho_s \tag{1}$$

where  $V_0$  and  $V_f$  are the velocities of the material at the die level and freeze-line level, respectively; and  $\rho_m$  and  $\rho_s$  are the melted and solid polymer densities, respectively. Using dimensionless parameters as defined in Table 2, Equation (1) can be written as:

$$\frac{1}{TR} = \frac{(R_0 + H_0) - R_0^2}{2R_0 H_0} \left( \frac{\rho_m}{\rho_s} \right) \frac{1}{DR \cdot BUR} \tag{2}$$

From Equation (2), a linear relationship exists between  $TR^{-1}$  and  $(DR \cdot BUR)^{-1}$ . Figure 4 shows that Equation (2) holds true for all

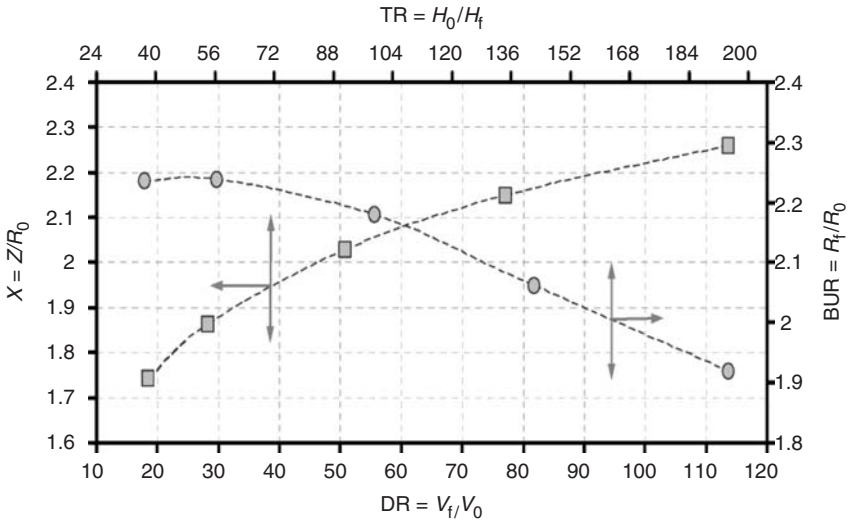


Figure 3. Experimental geometric data from LDPE blown film process.

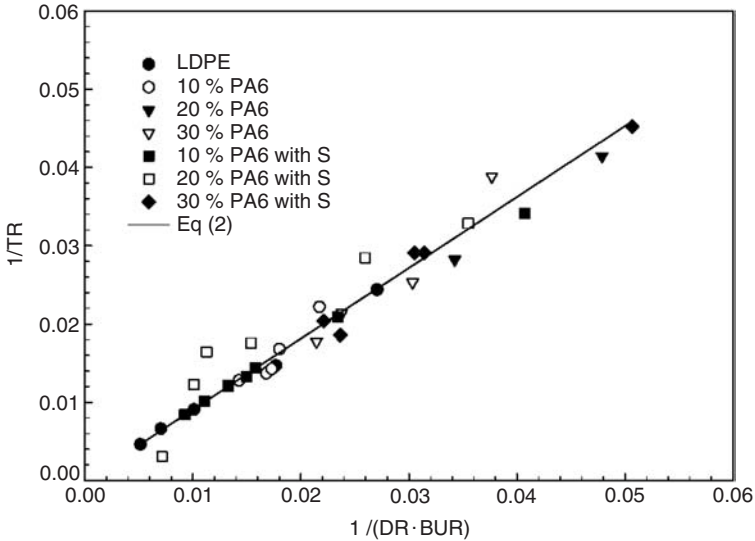


Figure 4. Relationship between  $TR^{-1}$  and  $(DR \cdot BUR)^{-1}$  for LDPE/PA6 blown films.

the film produced. From the data presented in Figure 4, a slope of  $0.91 \pm 0.02$  was obtained by linear regression. This value is in agreement with the theoretical value of 0.89 calculated from Equation (2) using the geometry and physical properties of the polymers [29].

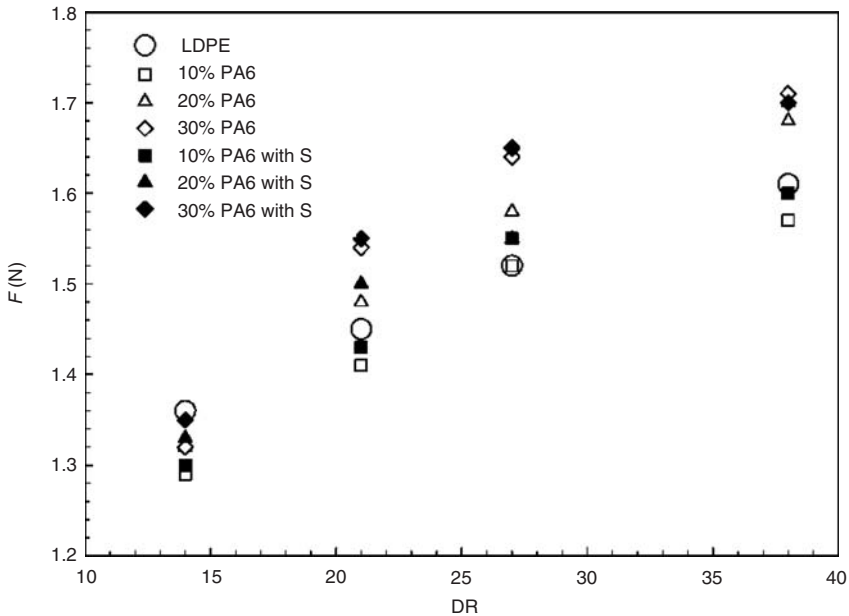
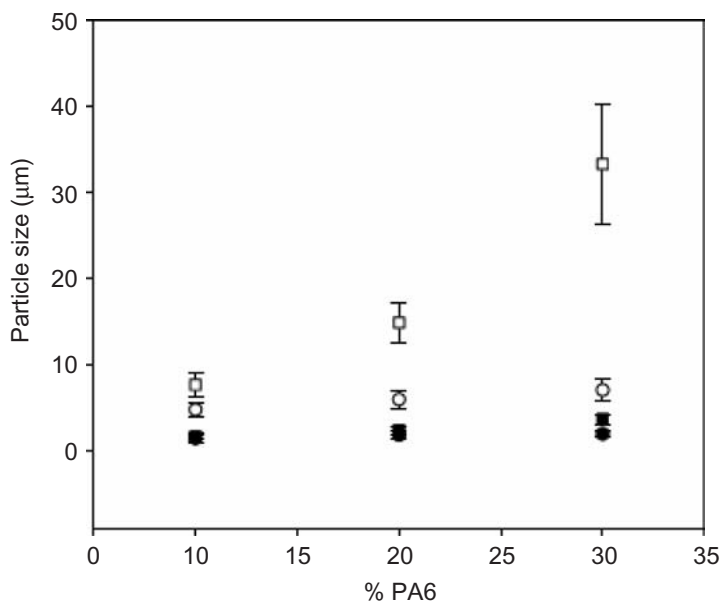


Figure 5. Experimental stretching force ( $F$ ) as a function of draw ratio (DR).

## Stretching Force Measurements

The take-up force ( $F$ ) measured is presented in Figure 5 as a function of DR. In all cases, the force slightly increases with DR although the cross-sectional area of the film decreases linearly with DR as described by Equation (2). Münstedt et al. [23] explained this effect by the strong temperature change which decreases from melt temperature to the crystallization temperature at the freeze-line position. As the viscosity is a function of temperature, the effect of the smaller cross-section on the force is compensated by the increasing viscosity. This means the cooling effect has a strong influence on the take-up force. Recently this effect was considered [24] and the results also showed that stretching force increased with increasing DR and/or decreasing freeze-line position. From Figure 5, it can be seen that PA6 content has little influence on the force measured for un-compatibilized blends. In the case of compatibilized blends a negligible effect is observed. In all cases the forces measured are small (1.2–1.7 N), but consistent with values reported in other studies [23–25]. These forces can be related to the deformation of the dispersed phase as presented in the next sections.

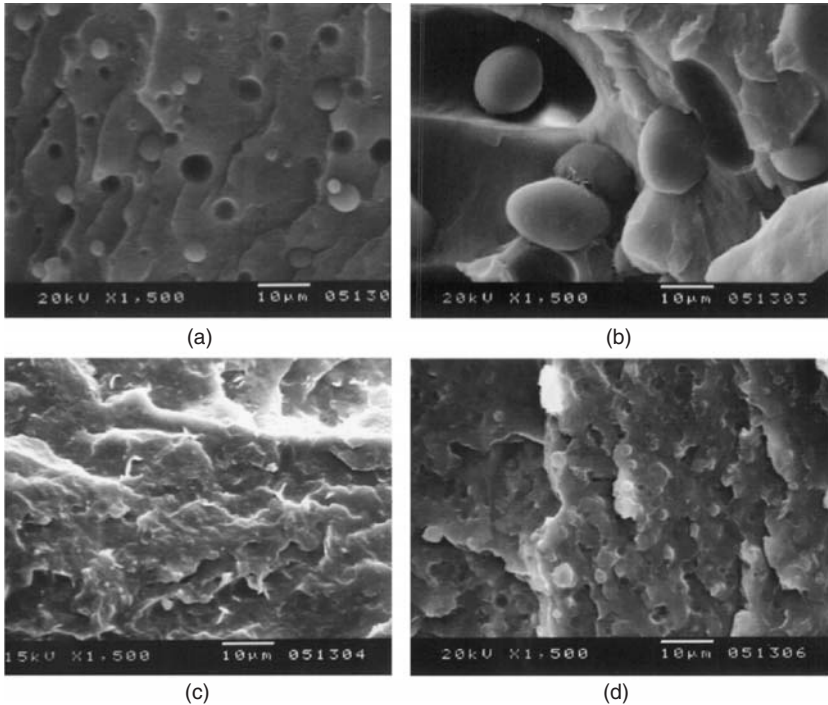


**Figure 6.** Average diameters of PA6 particles in LDPE blends prepared with (●, ■) and without (○, □) compatibilizer at the exit of (●, ○) first (twin-screw) and (■, □) second (single-screw) extruders.

## Morphology of Blends

Figure 6 shows the average diameter of the dispersed phase at the exit of the twin-screw (initial compounding) and single-screw (film processing) extruders. From Figure 6 it can be concluded that particle coalescence occurs in the second extrusion, i.e., particles sizes at the exit of the single-screw extruder are larger for non-compatible blends, especially when PA6 content is high (30%). These results indicate that the presence of the compatibilizer stabilizes the morphology, i.e., particle size does not increase significantly with reprocessing. Similar results were reported by *Íñiguez et al.* [30] for the system PET/HDPE.

Figure 7 shows the morphology of the blends at the exit of the single-screw extruder. For blends without compatibilizer (Figure 7(a), (b)), a well-defined morphology is obtained (coarse particle sizes). However, when a compatibilizer is incorporated into the blend, a substantial decrease in particle size is observed (Figure 7(c), (d)). Several studies have shown that Surlyn<sup>®</sup> 9020 is a very good compatibilizer for PE/PA6 blends because PA6 undergoes an amidation reaction with the carbonyl groups of the terpolymer

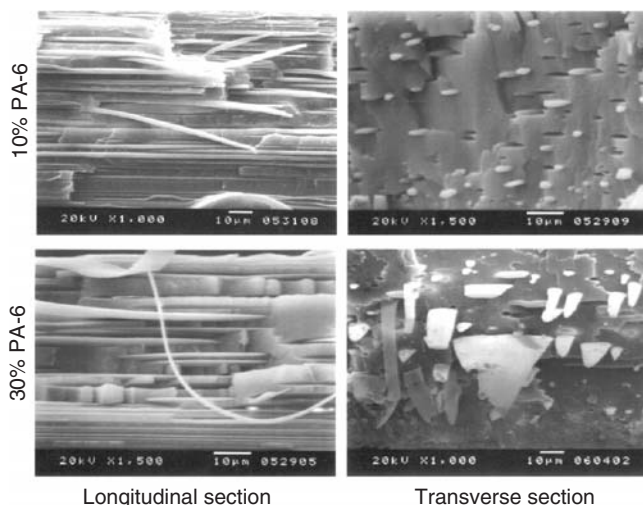


**Figure 7.** SEM micrographs taken at exit from extruder of PA6/LDPE blends with (a) 10% PA6 without compatibilizer, (b) 30% PA6 without compatibilizer, (c) 10% PA6 with compatibilizer, and (d) 30% PA6 with compatibilizer.

(Surlyn) [6,11]. Copolymers produced by this reaction are located at the interface and act as interfacial agents [11]. By decreasing interfacial tension, they allow better stress transfer from the matrix to the disperse phase, promoting particle disintegration.

### *Morphology of blown films*

The final morphology of the blown films is a direct result of the biaxial elongational flow pattern related to the blowing process. In Figure 8, the microscopic structure of non-compatible films is presented. At low PA6 content (10%), elongated fibers morphologies are produced; while at higher PA6 content (30%), the minor phase forms lamellas and deformations in both directions (MD and TD). Nevertheless, deformation in the MD is always higher compared to that of the TD. This induces an orientation in the MD of the films and the lamellas leading to anisotropy (Table 3) and as reported elsewhere [8,10,19].



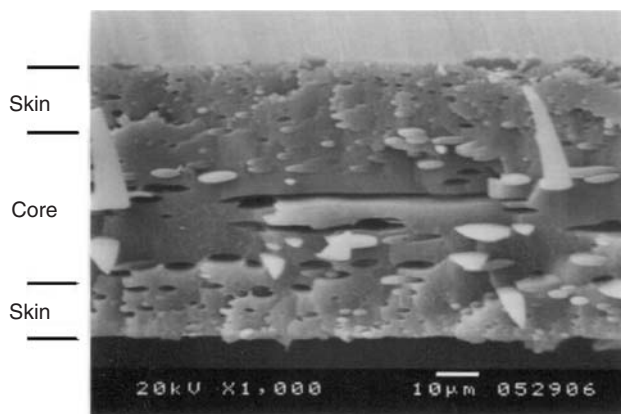
**Figure 8.** SEM micrographs of films prepared from non-compatible PA6/LDPE blends. BUR = 2.5, DR = 20.

More interesting is the presence of a skin/core morphology in the transversal section of the films as presented in Figure 9. In the skin zone, small elongated particles are present; while in the core zone, particles are larger due mainly to particle deformation. Fellahi et al. [16] observed an apparent sandwich structure consisting of three regions by shearing PA6/HDPE blends: (1) an isotropic skin where the dispersed phase particles are small, (2) an intermediate zone (sub-skin) where the particle sizes are maximum, and (3) an oriented core where deformation is maximum. It is well known that for pure shear flows (channel flow), stress is maximum near the walls and tends to zero at the core explaining that particle disintegration and dispersion is favored near the walls [31]. For film blowing, the process is mainly elongational and shear components are negligible in the stress field. Nevertheless a singularity is present at the annular die exit where the superficial layer of the melt is accelerated from zero (no slip condition at the die wall) to a finite velocity, creating an intense stretching of the external layer generating inhomogeneities in the material microstructure [32]. Considering the superficial layers and the bulk flow lines near the die exit, it can be seen that the material flow pattern induces higher disintegration and dispersion of the PA6 particles in the superficial layers than in the bulk region.

Table 3. Mechanical properties of the produced films at 25°C and 50% RH.

Blend (%PA6)	DR	Tensile strength (MPa)		Elongation at break (%)		Elastic modulus (MPa)		Tensile anisotropy $\alpha$ Equation (3)
		MD	TD	MD	TD	MD	TD	
LDPE	18.4	11.5 ± 1.6	7.7 ± 0.6	298 ± 22	166 ± 110	133 ± 20	122 ± 5	1.5
	29.0	15.6 ± 3.0	9.1 ± 1.7	187 ± 45	224 ± 153	122 ± 14	110 ± 10	1.7
	50.5	31.9 ± 1.6	20.1 ± 6.7	151 ± 28	300 ± 150	107 ± 4	96 ± 5	1.6
10% without Surllyn	19.9	12.3 ± 1.5	4.1 ± 0.4	410 ± 172	99 ± 55	174 ± 11	162 ± 7	3.0
	25.4	14.4 ± 1.2	5.6 ± 0.7	199 ± 83	74 ± 36	158 ± 16	153 ± 5	2.6
	32.3	16.7 ± 1.0	6.8 ± 0.6	127 ± 20	36 ± 12	156 ± 13	126 ± 6	2.5
30% without Surllyn	12.6	14.8 ± 2.0	4.5 ± 0.4	504 ± 80	11 ± 0.6	187 ± 13	146 ± 12	3.3
	20.3	22.0 ± 2.0	5.4 ± 1.3	458 ± 86	36 ± 4.0	171 ± 23	123 ± 12	4.0
	36.2	22.8 ± 4.2	—	469 ± 62	—	137 ± 8	—	—
10% with Surllyn	10.6	12.7 ± 3.5	7.6 ± 1.0	449 ± 92	350 ± 96	192 ± 18	177 ± 15	1.7
	25.5	15.1 ± 2.0	9.3 ± 0.9	359 ± 60	210 ± 34	185 ± 16	164 ± 13	1.6
	36.6	19.2 ± 1.1	11.0 ± 0.8	212 ± 23	120 ± 103	170 ± 15	154 ± 11	1.7
30% with Surllyn	12.3	15.7 ± 1.2	8.2 ± 0.8	365 ± 52	48 ± 8.7	238 ± 12	194 ± 16	1.9
	19.2	25.3 ± 2.6	11.2 ± 0.6	407 ± 80	27 ± 2.5	230 ± 6	185 ± 8	2.2
	34.5	28.0 ± 2.9	15.27 ± 0.4	258 ± 158	24 ± 2.1	224 ± 16	168 ± 9	1.8

MD = machine direction; TD = transverse direction; DR = draw ratio.

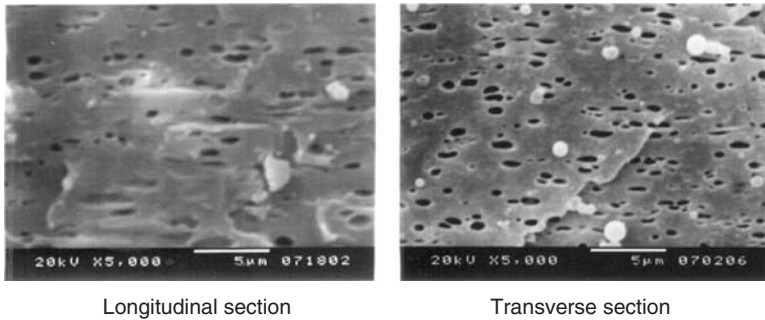


**Figure 9.** Skin-core structure generated during elongational flows in films prepared from non-compatible PA6/LDPE blends. BUR = 2.5, DR = 20.

The morphology of the compatibilized films is substantially different from that of the noncompatibilized films. Because of smaller sizes and better distribution, coalescence is low. Without coalescence, spherical particles dispersed in a fluid subjected to a biaxial deformation field will deform into ellipsoidal shapes as a function of the applied stress (see Figure 10). Ellipsoidal particles stretch until they break into two or more minor particles [32]. Further work on the modeling of the disperse particles deformation is not included here but is currently under way and will be the subject of a future report.

### Tensile Properties of Blown Films

Results obtained from tensile tests were used to determine the tensile strength (nominal), elongation at break, and elastic modulus of the films. Table 3 presents the results as a function of DR for these LDPE films – note should be made that the BUR was maintained between 1.9 and 2.3 for all these tests (see Figure 3). Polymer molecular chain orientation has a great influence on the final mechanical properties of polymeric films, especially when they are prepared with semi-crystalline polymers, such as LDPE and PA6 [4]. An increase in DR promotes polyethylene chain orientation in the MD, leading to increased elastic modulus and tensile strength for a low DR (<15) [21]. In this study, high DR ( $10 < DR < 50$ ) values were used, and a diminution in both MD and TD elastic modulus with DR was observed. LDPE/PA6 blends behaved differently when compared to neat LDPE films. Analyzing the micrographs (Figure 8), one can observe that PA6 fibers (or lamellas)



**Figure 10.** SEM micrographs of films prepared from compatibilized PA6/LDPE blends. BUR = 2.5, DR = 20.

in the LDPE matrix are oriented in the flow direction (MD). In general, PA6 has better mechanical properties than LDPE, even more when the polymeric chains are oriented and this leads to greater tensile anisotropy. In addition, it can be noted that non-compatible films have lower modulus compared with their compatibilized counterparts.

The presence of the compatibilizer affects the tensile properties of the films (Table 3). At high PA6 content, tensile properties in the MD are higher for compatibilized films than for non-compatible ones. From a morphological comparison between both films (Figures 8 and 10) it can be concluded that PA6 fibers supply more strengthening to non-compatible films in the MD. In the TD, the reverse has been observed, especially for low DR values [21].

Differences between tensile properties observed in longitudinal and transversal directions reflect the anisotropic nature of the films. A definition of the degree of anisotropy ( $\alpha$ ) is [10]:

$$\alpha = \frac{\sigma_{pL}}{\sigma_{pT}} \quad (3)$$

where  $\sigma_{pL}$  and  $\sigma_{pT}$  are the tensile strength in the MD and TD, respectively. In this way, when  $\sigma_{pL} \approx \sigma_{pT}$ ,  $\alpha \approx 1$  and the film is isotropic. On the other hand, when  $\sigma_{pL}/\sigma_{pT} \rightarrow \infty$ , high anisotropy is obtained and very low tensile properties are observed in the TD. Zhang et al. [10] observed that LDPE films have an anisotropy of 2 for DR = 23. In this case, anisotropy between 1.2 and 4.4 were observed for the range of DR values. From Equation (3),  $\alpha = 1.5$  for LDPE and remained constant for DR values higher than 100. From La Mantia et al. [21], it is possible to calculate  $\alpha$ -values for their compatibilized PA6/LDPE (20% of PA6) that are close to 2 for DR < 14 and BUR = 2.55. Table 3 shows the degree

**Table 4. Permeability ( $P$ ) at  $\approx 25^\circ\text{C}$  of toluene as a function of PA6 content for films prepared with and without compatibilizer. ( $DR \approx 20$  and  $BUR \approx 2.2$ ).**

PA6 content (%)	$P$ ( $\times 10^7$ m · mol · cm/cm <sup>2</sup> · s)			
	0	10	20	30
Without compatibilizer	25 ± 5	23 ± 3	15 ± 2	7.0 ± 2
With compatibilizer	–	10 ± 2	3.0 ± 1.5	1.0 ± 0.5

of anisotropy as a function of DR for the LDPE/PA6 films, with and without compatibilizer. It can be seen that films having highly disordered morphologies (i.e., 30% PA6 without compatibilizer) present higher  $\alpha$  values ( $\approx 4.0$ ); while lower  $\alpha$ -values (1.2–1.6) are obtained for films presenting more ordered morphologies (i.e., 10% PA6 with compatibilizer).

### Barrier Properties of Blown Films

Blends containing PA6 have been extensively used for their excellent barrier properties to hydrocarbons. In most cases the blends were prepared by compression or blow molding [12,13,15,17]. Reports on barrier properties of blown films prepared by HDPE/PA6 multilayer structures are available [33]. For packaging applications, permeability and tensile strength are the two most important properties. Here film permeability to toluene was evaluated. Toluene was used as a representative non-polar hydrocarbon, which is often used as paint thinner and in various commercial products [13].

The permeability of toluene for compatibilized and un-compatibilized blends is reported in Table 4. The results indicate that permeability of un-compatibilized films decreases with increasing PA6 content; while there is even a larger decrease in permeability with increasing PA6 content for compatibilized blends because of the larger surface area of the dispersed phase (PA6) with its high barrier properties as was also shown elsewhere [12,13]. In the biaxial flow generated during film blowing, PA6 particles are deformed into extended lamellas, especially at high PA6 content (Figures 7 and 8). Such lamellas make the solvent trajectory more tortuous. Subramanian [13] showed that the formation of lamellar morphologies enhanced the barrier properties for PA6/HDPE blends. Furthermore, Figure 6 shows that the morphology of uncompatibilized blends presented some voids between each component; while none were observed for compatibilized systems. This better adhesion between each phase can also explain the differences in permeability. In previous studies

on PA6/HDPE blends prepared by ribbon extrusion, the efficiency of blends and alloys (compatibilized blends) were verified as barrier materials to several solvents [6]. The results showed that permeability decreased with increasing size of the permeate molecules ( $\text{CH}_2\text{Cl}_2$ ,  $\text{CHCl}_3$ , and  $\text{CCl}_4$ ) and the effect was more important for compatibilized blends.

## CONCLUSIONS

The amount of PA6 and the presence of a compatibilizer were found to modify substantially the mechanical and barrier properties of LDPE blown films. The deformation of the dispersed phase induced by the blowing process is the main reason explaining the improved properties. Blends with high PA6 content (30%) result in large domain morphologies, which in turn results in lamellar morphologies when the blends are biaxially stretched. These kinds of microstructures and a better interfacial adhesion (with compatibilized blends) considerably reduce permeability. Fiber morphology is produced at low PA6 content (10%) improving tensile properties due to the higher strength of PA6. Draw ratio was found to affect directly the structure, providing orientation predominantly in the MD (fiber alignment). These morphologies produced a difference in the normal stresses, which make the material anisotropic. The degree of anisotropy was quantified in relation with the tensile strength in the MD and TD. It was found to depend on PA6 content, compatibilizer presence, and processing conditions.

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