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Mechanical and morphological properties of high density polyethylene and polylactide blends

Abstract: Polyblend films were prepared from high-density polyethylene (HDPE) and poly(L-lactic acid) (PLLA) up to 20% PLLA by the melt blending method in an extrusion mixer with post-extrusion blown film attachment. The 80/20 (HDPE/PLLA) blend was compatibilized with maleic anhydride grafted polyethylene (PE-*g*-MA) in varying ratios [up to 8 parts per hundred of resin (phr)]. Tensile properties of the films were evaluated to obtain optimized composition for packaging applications of both non-compatibilized and compatibilized blends. The compositions HDPE80 (80% HDPE and 20% PLLA) and HD80C4 (80% HDPE, 20% PLLA and 4 phr compatibilizer) were found to be optimum for packaging applications. However, better tensile strength (at yield) and elongation (at break) of 80/20 (HDPE/PLLA) blend were noticed in the presence of PE-*g*-MA. Further, thermal properties and morphologies of these blends were evaluated. Differential scanning calorimetry (DSC) study revealed that blending does not much affect the crystalline melting point of HDPE and PLLA, but heat of fusion of 80/20 (HDPE/PLLA) blend was decreased as compared to that of neat HDPE. Spectroscopy studies showed evidence of the introduction of some new groups in the blends and gaining compatibility in the presence of PE-*g*-MA. The compatibilizer influenced the morphology of the blends, as apparent from scanning electron microscopy (SEM) and supported by Fourier transform infrared (FTIR).

Keywords: DSC; HDPE/PLLA blends; morphology; tensile; XRD.

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1 Introduction

Conventional petroleum-based packaging plastics are versatile, relatively economical, easily processed, have excellent properties and are resistant to degradation, which is why they are used extensively. High-density polyethylene (HDPE), low-density polyethylene (LDPE) and polypropylene (PP) are some of those synthetic plastics which are widely used as packaging films (carrier bags), mulching films and for similar other purposes [1]. HDPE contains carbon and hydrogen as backbone elements and has little branching; it also has stronger intermolecular forces and tensile strength than LDPE. Physically, it is harder, more opaque, can withstand somewhat higher temperatures and therefore, has extensive industrial and day-today applications. However, with the expanding range of products, the consumption of these plastics is increasing incessantly, but the plastic waste gets accumulated abundantly in the environment causing “white pollution”, plastic waste management problems, perceived garbage crisis, shortage of landfills etc. [2]. Annually, about 500 billion to 1 trillion polythene carrier bags are used around the globe and 25 million tons of synthetic plastics accumulate in the sea coasts and terrestrial environment every year [3]. In particular, approximately 61 thousand tons of plastic wastes found their way in to India in the year 2000 [4]. However, with these drastic rises in the use of plastic materials, a corresponding development of processes for the harmless disposal or degradation of the plastic waste has not been noticed. Recycling of plastic waste is one of the solutions for this, but the cost of recycling is very high and the recycled products have inferior qualities [5]. Moreover, the shortage and depletion of petroleum resources over the years have driven efforts to produce biodegradable packaging materials and develop partially biodegradable blends or alloys of bio- and petrochemical-based materials (called hybrid bioplastics). In particular, renewable agricultural and biomass feedstock has shown much promise for use in eco-efficient packaging to replace petroleum feedstock without competing with food crops [6]. Biobased and biodegradable polymers have a wide range of applications, such as in the packaging, biomedical and agricultural fields. The most common

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of the biodegradable materials are poly(lactic acid) or polylactides, polycaprolactone, poly(butylene adipate terephthalate) and polyhydroxybutyrate. In this regard, poly(L-lactic acid) (PLLA), which benefits both from coming from renewable resources and being biodegradable in the compost environment [7], having functions such as hydrolysis, and thermal depolymerization [8, 9] has attracted much attention. It has become an economically viable commodity plastic in industry and is employed to produce flexible packaging films for the food packaging industry, in addition to the common-use articles such as trays and bottles etc. [10–12]. However, there are some limitations to PLLA usage in the packaging industry, which include low thermal stability, medium gas-barrier properties and brittleness [13].

Blending of a non-biodegradable polymer with a biodegradable one is a well-established approach employed by many researchers [14–19] for obtaining degradable materials for sustainable development and specific end-uses. Total replacement of the commercial polymers for packaging applications by the completely biodegradable ones is remote, due to the use of costly monomers and additives in the expensive production/processing of the biodegradable biopolymers and the limited shelf life of biodegradable polymers. Moreover, attaining high performance properties of the former by the latter is not yet possible. To overcome these limitations, partially degradable polymers have been developed with a negotiation between cost and performance [20–22]. Therefore, the investigations concerning the total or partial substitution of synthetic plastics by biodegradable materials have proven to be very useful in solving the problem of plastic waste management to a significant extent [8, 14, 15, 23–27].

Polymer blends and composites containing natural polymers (such as starch, cellulose and their derivatives) as biodegradable additives were developed [28–30], which were easily extrudable and commercialized. However, the major disadvantage of blending natural polymers into synthetic polymers is their compatibility, resulting in the poor interaction between matrix and filler interphase; this in turn results in inferior mechanical properties [31–33]. Moreover, the natural polymers cause processability problems during production of films from the blends [33]. Even in the case of HDPE and PLLA, because of the difference in their chemical structures, these are immiscible and exhibit weak interfacial adhesion in their binary blends. In order to improve interactions between immiscible polymers, addition of a suitable compatibilizer can increase the morphological stability and interfacial adhesion, and result in better ultimate mechanical properties of the blends [34]. Reactive interfacial coupling agents are frequently used to improve interfacial properties and control morphologies of polymeric blends, as the coupling agents containing reactive functional groups are able to generate *in situ* formation of grafted copolymers at the interface [35].

There have been very limited reports on producing partial biodegradable blends of HDPE for packaging applications, but some researchers have worked on this imperative subject. Grafted maleic anhydride as a polar monomer has been used widely to modify nonpolar polymers to improve the interfacial linkage between the immiscible polymers. HDPE was blended with chitosan by a peroxide-initiated melt compounding technique using vinyl triethoxysilane as crosslinker. It was found that the tensile strength of crosslinked HDPE/chitosan blends containing 35% chitosan contents was 27.4 MPa, which was three times higher than the crosslinked HDPE and a good compatibility and strong adhesion between HDPE and chitosan interphase was noticed [36]. The compatibilizing effect of immiscible HDPE/Nylon-6 blends was studied with varying styrene/ethylene–butylene/styrene triblock polymer and maleic anhydride grafted polyethylene (PE-*g*-MA) concentrations and it was found that impact performance and interfacial bonding between banana fiber and the resins was enhanced by using the compatibilizers [37]. PE-*g*-MA was considered for the present investigation on the basis of wide use of grafted MA as a compatibilizer in binary immiscible polymer blends [38–43].

This study is aimed to develop partially biodegradable packaging films of HDPE/PLLA blends and characterize their physicomechanical and morphological properties. The thermal properties of the blends are also evaluated and the effect of adding PLLA and compatibilizer on these performance factors is also analyzed.

2 Materials and methods

2.1 Materials

All of the materials used in this study were available commercially. Film grade HDPE (trade name G-Lex F55HM0003) with a density of 0.955 g/ml was purchased from GAIL India Limited (Kolkata, India). PLLA (trade name Biomer L9000) with M_w=20 kDa and M_n=10.1 kDa was supplied by Biomer Forst-Kasten-Str Kailling, Germany. PE-*g*-MA (trade name Optim E142) with a density of 0.925 g/ml was obtained from Pluss Polymers Pvt., Ltd. (New Delhi, India).

2.2 Blends preparation

The melt blending of HDPE and PLLA with/without PE-*g*-MA, in varying ratio(s), was prepared in a single screw extruder of Haake Rheocord, Burladingen, Germany, with a screw diameter of 19.05 mm and length-to-diameter ratio of 25. The temperature profile of the extruder was set at 125°C, 185°C and 190°C from feed inlet to die, respectively. The polymers were manually premixed (before blending) in the desired compositions as described in Table 1. Subsequently, the blends were blown to their respective films of 30 μm thickness from the post-extrusion blown film system mounted to the abovementioned extruder equipped with a film die with a diameter of 30 mm and die gap of 0.8 mm. The blow up ratio (BUR), defined as the ratio of the diameter of the final film tube to the diameter of the die, was 3:1. The draw down ratio (DDR), which is the ratio of the film velocity at the nip roll to the initial polymer velocity at the die exit, was kept at 10. The resin temperature at die exit was held at 190°C and the throughput at 2.5 kg/h. All films were extruded with a constant drawing rate of 200%–250% to a consistent width of 100 mm. The thickness of the prepared films was measured using a dial thickness gauge 7301, Mitutoyo, Japan at an accuracy of ±5 μm.

2.3 Mechanical properties (tensile testing)

The tensile tests – tensile strength at yield and elongation at break – were performed at room temperature on a Zwick-Roell Universal Testing Machine, Model Z010, Zwick-Roell, Germany, according to the procedure of ASTM D 882, using rectangular shaped specimens. The grip to grip separation of the samples having a 25.4 mm gauge length was 100 mm at the start position. A crosshead speed of 50 mm/min was maintained. At least three specimens of each blend were tested and the average values were reported.

Table 1 Names and composition of high-density polyethylene (HDPE)/poly(L-lactic acid) (PLLA) blends with/without compatibilizer.

S. no.	Sample name	HDPE (wt%)	PLLA (wt%)	PE-*g*-MA (phr)
1.	HDPE100	100	0	0
2.	HDPE95	95	5	0
3.	HDPE90	90	10	0
4.	HDPE85	85	15	0
5.	HDPE80	80	20	0
6.	HD80C2	80	20	2
7.	HD80C4	80	20	4
8.	HD80C6	80	20	6
9.	HD80C8	80	20	8

PE-*g*-MA, maleic anhydride grafted polyethylene.

2.4 Differential scanning calorimetry

The melting and crystallization behaviors of HDPE/PLLA blends were evaluated by differential scanning calorimetry (DSC) performed with Netzsch DSC apparatus (model DSC 200F3 Maia) under nitrogen atmosphere. The temperature for the DSC thermal history was varied from -135°C to 300°C at a rate of 10°C/min as per the thermal history shown in Figure 1. The transition temperatures and peak areas of the samples were determined by using the data obtained by the software and the standard graphical analysis tools. The degree of crystallinity (χ_c) was calculated according to Eq. (1) as follows [21]:

$$\chi_c = (\Delta H_f^{cal} / \Delta H_f^{s}) \times 100 \tag{1}$$

where ΔH_f^{cal} is the calculated heat (J/g) of fusion values and ΔH_f^{s} are standard heat of fusion values for 100% crystalline HDPE (287 J/g) or PLLA (93 J/g).

2.5 X-ray diffraction analysis

In order to understand the chemical composition and crystallographic structure of a material, X-ray diffraction

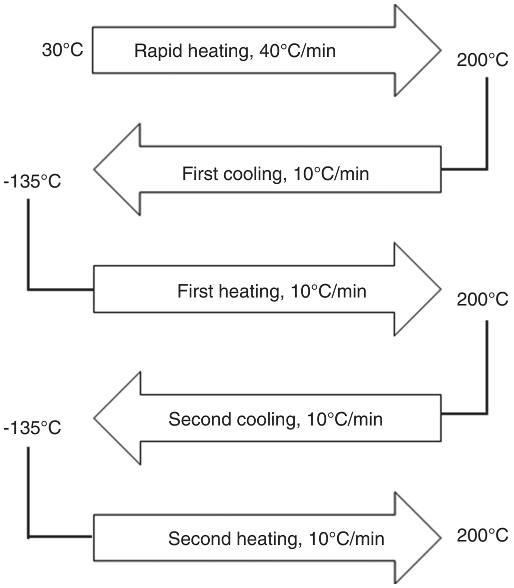

Figure 1 Differential scanning calorimetry (DSC) thermal history of samples.

(XRD) is a versatile and nondestructive technique. The XRD patterns were recorded at room temperature using a Philips Xpert diffractometer (Almelo, Netherlands) with monochromatic CuKα radiation (λ=1.5418 Å) operating at 40 kV and 20 mA. Monochromatic X-rays are applied to identify the interplanar spacing in any unknown substance. During the test, the scanning speed was kept at 5°/min and the diffraction angle (2θ) was 5°–60°. The software 'High Score' was used to calculate crystallinity (%), which was provided by Xpert.

2.6 Fourier transform infrared spectroscopy

In order to determine the formation of new or disappearance of functional groups in the prepared blends, Fourier transform infrared (FTIR) spectroscopic studies were carried out on the film samples with a Perkin Elmer FTIR spectrophotometer (model BX-II, Shelton) with a zinc selenide crystal. A total of 16 scans/sample were taken, with a resolution of 4 cm^{-1} and the obtained spectrum was analyzed with the spectrum software (LX100627-I, Shelton).

2.7 Scanning electron microscopy

In scanning electron microscopy (SEM) studies, a JEOL JSM 5800 scanning electron microscope operating at a 20 kV accelerating voltage, was used to observe blend morphology. The surfaces taken from cryofractured samples were examined. In order to prepare cryofractured samples, the films were plunged in liquid N_2 into a stable, insulated vessel while holding with tweezers. The films were removed after the bubbling stopped and then broken into two pieces. The samples were then coated with a 50 µm thin layer of gold using a sputtering coater before putting them into the microscope. Finally, the SEM micrographs of the cryofractured surfaces were analyzed to characterize the microstructures of the samples.

3 Results and discussion

3.1 Mechanical properties

For evaluating the tensile properties of HDPE/PLLA blends and analyzing the effect of PE-*g*-MA on those performance parameters of the 80:20 (HDPE/PLLA) blend, the tensile strength at yield and elongation at break were measured. Table 2 summarizes the tensile strength at yield and the breaking elongation of the blends as a function of their respective composition.

Table 2 Tensile strength (at yield) and elongation (at break) of the blends.

S. no.	Sample	Tensile strength at yield (MPa)	Elongation at break (%)
1.	HDPE100	45.30 ±2.4	255 ±28
2.	HDPE95	26.60 ±0.8	245 ±24
3.	HDPE90	22.13 ±2.3	220 ±12
4.	HDPE85	17.10 ±1.6	170 ±25
5.	HDPE80	13.53 ±1.1	96 ±9.5
6.	HD80C2	17.57 ±1.5	103 ±20
7.	HD80C4	19.90 ±1.9	147 ±16
8.	HD80C6	32.50 ±2.0	161 ±15
9.	HD80C8	52.70 ±3.7	188 ±19

Figures 2 and 3 show the changes in tensile strength at yield and elongation at break, respectively, by varying HDPE/PLLA composition in the blends. Tensile properties are related to the degree of molecular orientation, the molecular weight of the polymer, degree of crystallinity and the glass transition temperature [44]. These properties of the blended films showed a decreasing trend with increasing PLLA content. This effect is attributed to the brittle nature of PLLA. It was observed that up to 20% PLLA addition to the HDPE matrix, the decrease in the tensile properties was comparatively smaller. As PLLA shows stress-induced crystallization (SIC) behavior upon drawing above glass transition temperature [45], therefore,

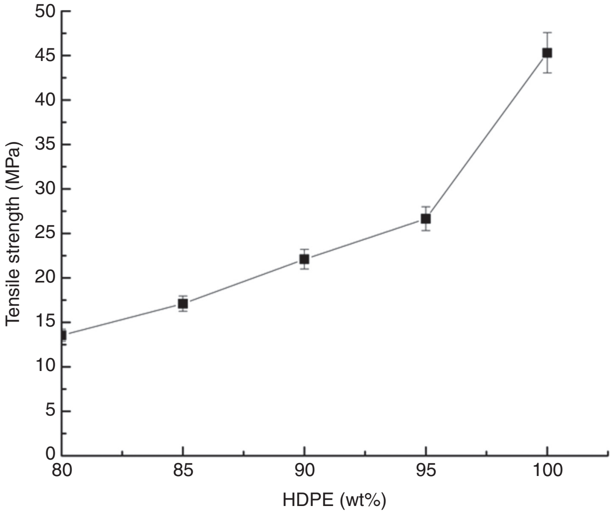

Figure 2 Changes in tensile strength with varying high-density polyethylene (HDPE)/poly(L-lactic acid) (PLLA) composition in the blends.

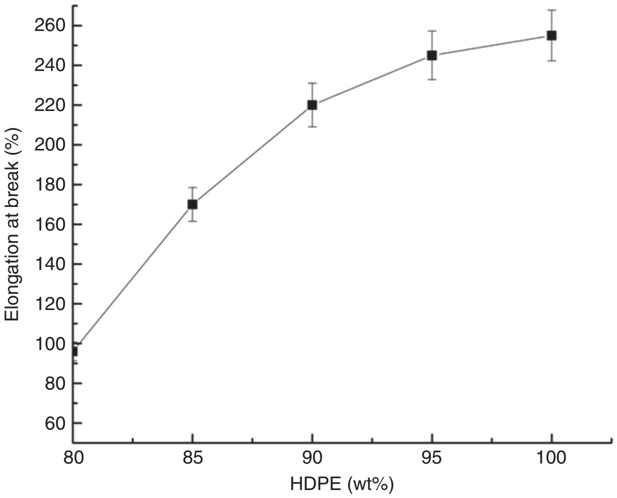

Figure 3 Changes in % elongation (at break) with varying high-density polyethylene (HDPE)/poly(L-lactic acid) (PLLA) composition in the blends.

the small decrease in tensile properties of HDPE/PLLA blends (up to 20% PLLA only) may be endorsed to the SIC of PLLA, including interfacial adhesion and chain entanglement with HDPE during post-extrusion blown film in melt blending. Similar results were noticed by Singh et al. [25] for the LLDPE/PLLA system. However, on further increasing the amount of PLLA, this brittle polymer turned out to be more prevailing, resulting in a drastic decline of these properties. Hence, in view of better retention of mechanical properties, we selected the HDPE80 blend for further study and the effects of compatibilizer PE-*g*-MA from 2 parts per hundred of resin (phr) to 8 phr loading on the polymeric blend HDPE80, were examined.

Figures 4 and 5 show the changes in tensile strength at yield and elongation at break, respectively, by varying the PE-*g*-MA composition in HDPE80. The tensile strength at yield of the blend containing 4 phr PE-*g*-MA, i.e., HD80C4, increased from 13.55 MPa to 19.90 MPa as compared to HDPE80. This was probably due to the fact that addition of the compatibilizer improved the dispersion in the blend, leading to a better interaction between the phases. In blends containing PE-*g*-MA, elongation at break increased with increasing concentration of PE-*g*-MA at all compositions. The % elongation of HD80C4 increased to 147% against 96% of HDPE80. This may be attributed to the better interfacial interaction and improved plasticity of the blend by assimilation of the compatibilizer. However, 6 phr and 8 phr addition of the compatibilizer further increased these values, but 4 phr compatibilizer was taken as optimum, because of economic reasons. Hence, the blends HDPE80 (without compatibilizer) and HD80C4 (with compatibilizer) showed acceptable mechanical properties for packaging applications. Improvement in the tensile strength at yield and elongation with the addition of PE-*g*-MA was an interesting feature of these blends and suggests that PE-*g*-MA behaved as a good compatibilizer for HDPE/PLLA blends.

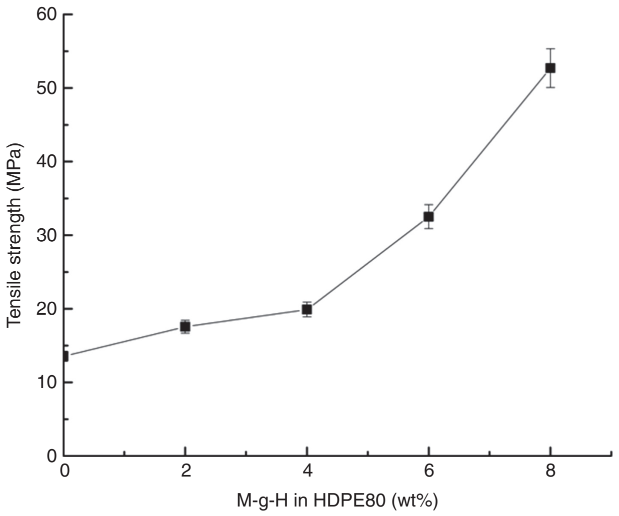

Figure 4 Changes in tensile strength (at yield) by varying the maleic anhydride grafted polyethylene (PE-*g*-MA) composition in 80% high-density polyethylene (HDPE) and 20% poly(L-lactic acid) (PLLA) (HDPE80) blend.

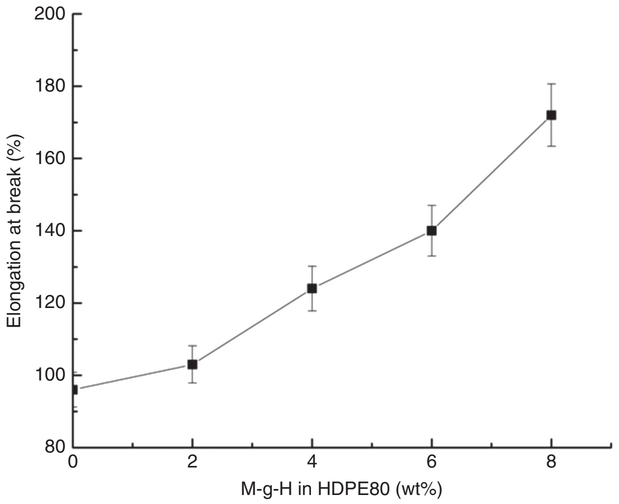

Figure 5 Changes in % elongation (at break) by varying the maleic anhydride grafted polyethylene (PE-*g*-MA) composition in 80% high-density polyethylene (HDPE) and 20% poly(L-lactic acid) (PLLA) (HDPE80) blend.

3.2 DSC analysis

The heating and the cooling curves obtained from calorimetry of HDPE100, HDPE80, HD80C4 and PLLA100 are

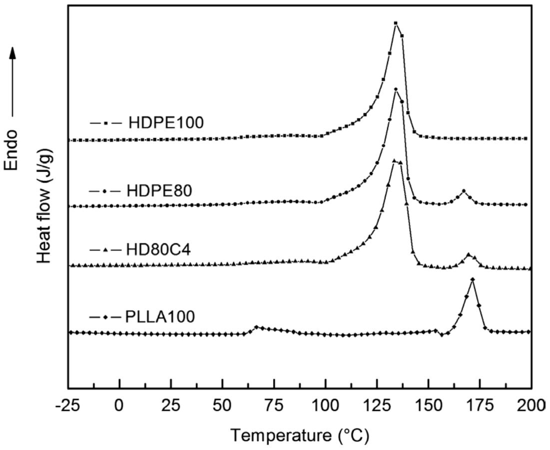

Figure 6 Differential scanning calorimetry (DSC) heating curves showing the crystallization melting temperature of 100% high-density polyethylene (HDPE) (HDPE100), 80% HDPE and 20% poly(L-lactic acid) (PLLA) (HDPE80), 80% HDPE, 20% PLLA and 4 phr compatibilizer (HD80C4) and 100% PLLA (PLLA100).

shown in Figures 6 and 7, respectively. The melting endotherms and crystallization exotherms were used to characterize the following parameters:

1. T_m – crystalline melting point analogous to first heating and second heating, °C;
2. T_{onset} – onset temperature of melting and crystallization, respectively, °C;
3. T_c – crystallization temperature analogous to first cooling and second cooling, °C;
4. ΔH_c – enthalpy of crystallization, evaluated from the area under the exotherm, J/g;
5. ΔH_f – heat of fusion, measured from the area under the endotherm, J/g;
6. χ_c – degree of crystallinity (%) of HDPE and PLLA in blends, compared to 100% crystalline HDPE and PLLA [as per Eq. (1) above].

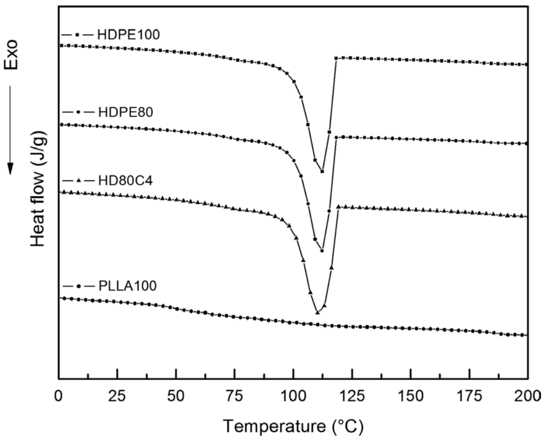

Figure 7 Differential scanning calorimetry (DSC) cooling curves showing the crystallization temperature of 100% high-density polyethylene (HDPE) (HDPE100), 80% HDPE and 20% poly(L-lactic acid) (PLLA) (HDPE80), 80% HDPE, 20% PLLA and 4 phr compatibilizer (HD80C4) and 100% PLLA (PLLA100).

The results are depicted in Table 3. It emerged from the table that the crystallization melting points (T_m) of neat HDPE and PLLA were 134°C and 171.7°C, respectively. However, the thermogram of their blends showed two melting endotherms, which corresponded to those of HDPE and PLLA phases, respectively. No significant 'peak shift' was noted with the addition of 4 phr PE-*g*-MA. This analysis showed that the compatibility between HDPE and PLLA was not very substantial. The onset crystallization temperature (T_{onset}) of neat HDPE was 120.1°C, whereas for blends, it went down to 101.7°C and 100.4°C for HDPE80 and HD80C4 blends, respectively. As PLLA is amorphous in nature, no onset crystallization temperature (T_{onset}) was noted for neat PLLA. It is also seen from Table 3, that the enthalpy of crystallization (ΔH_c) of neat HDPE was approximately equal to that of HDPE/PLLA blends and no effect by PLLA phase on ΔH_c was observed. Thus, maximum energy was liberated during crystallization of neat HDPE. This is due to the fact that in virgin HDPE, the nucleation and growth of individual crystallites are so rapid that a large number of crystallites are formed together and a large quantity of heat is liberated [46]. In the case of PLLA, by contrast, no crystallites were formed due to its amorphous nature. The values of heat of fusion (ΔH_f) of both HDPE and PLLA decreased upon blending, which might be because of a little degree of mixing and interaction between the polymer interfaces. The percent crystallinity of neat HDPE was found to be 66.3% and decreased to 65.16% when PLLA was blended in it. This value further decreased to 57.11% in the presence of 4 phr compatibilizer. However, neat PLLA, having no crystallinity so far, gained crystallinity upon blending with HDPE, which went up to 11.89% for the HDPE80 blend, which was probably due to SIC behavior of PLLA with HDPE during post-extrusion blown film in melt blending. HD80C4 may have had maximum interfacial entanglements that were trapped upon the melt crystallization of HDPE and PLLA.

3.3 XRD analysis

Figure 8 illustrates the XRD patterns of HDPE100, HDPE80 and HD80C4 blends. The diffractogram of HDPE showed diffraction peaks at 2θ=21.7° and 24.1°. These peaks were also detected in HDPE80, but the intensity was greater, hence, more crystalline. This could be attributed to the interaction, chain entanglement and crystallization

Table 3 Melting and crystallization behavior of high-density polyethylene (HDPE)/poly(L-lactic acid) (PLLA) blends.

Blend	Crystallization melting point of HDPE and PLLA (°C)		Onset temp. (°C) of HDPE and PLLA		Crystallization temp. (°C) of HDPE and PLLA		Enthalpy of crystallization ($-\Delta H_c$ J/g)	Heat of fusion ($-\Delta H_f$ J/g)		Crystallinity (%)	
	First heating	Second heating	Melting	Crystallization	First cooling	Second cooling		HDPE	PLLA	HDPE	PLLA
HDPE100	133.4	134.0	119.6	120.1	107.0	114.2	185.8	190.3	–	66.30	–
HDPE80	135.2	135.6	124.5	101.7	111.4	111.6	178.0	187.0	11.06	65.16	11.89
	168.1	167.8	161.4								
HD80C4	134.2	134.7	123.3	100.4	110.9	110.8	184.5	163.9	8.82	57.11	9.48
	173.7	173.3	167.7								
PLLA100	170.9	171.7	163.6	–	–	–	–	–	47.27	–	–

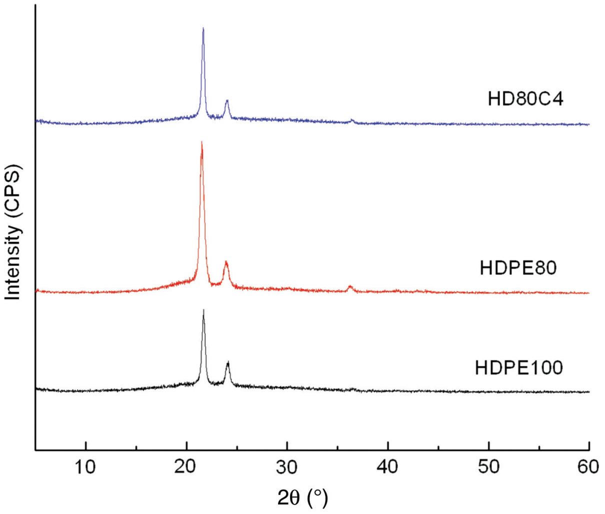

Figure 8 X-ray diffraction (XRD) spectra of 100% high-density polyethylene (HDPE) (HDPE100), 80% HDPE and 20% poly(L-lactic acid) (PLLA) (HDPE80) and 80% HDPE, 20% PLLA and 4 phr compatibilizer (HD80C4) blends.

behavior of PLLA with HDPE during the post-extrusion blown film in blending.

3.4 FTIR spectroscopy

FTIR spectra of the selected blends were taken in the region 500–4000 cm^{-1} and are shown in Figure 9. The strongest peak was observed for HDPE between 2922 cm^{-1} and 2856 cm^{-1} wave-number, and smaller peaks at 1470 cm^{-1} and 722 cm^{-1}. Peaks at 2922 cm^{-1} down to 2856 cm^{-1} are also noticed for HDPE80 and HD80C4 blends, but some more peaks at 1760 cm^{-1} down to 722 cm^{-1} were observed for these blends. The peaks observed in HDPE80 and HD80C4 spectra at 1760 cm^{-1} are assigned as carbonyl peaks.

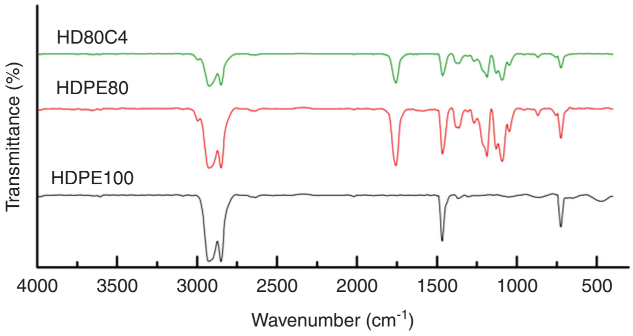

Figure 9 Fourier transform infrared (FTIR) spectra of 100% high-density polyethylene (HDPE) (HDPE100), 80% HDPE and 20% poly(L-lactic acid) (PLLA) (HDPE80) and 80% HDPE, 20% PLLA and 4 phr compatibilizer (HD80C4) blends.

Polymers containing carbonyl groups usually undergo some interaction (viz. hydrogen bonding), if they are compatible. Here, in the case of HDPE80 and HD80C4 blends, the new peaks introduced at 1760 cm^{-1} and several others between 1760 cm^{-1} and 722 cm^{-1} is evidence of the introduction of some new groups in the blends. A peak-shift of 10 cm^{-1} in the HD80C4 blend may be attributed to the hydrogen bonding interaction in the two phases of PLLA and HDPE in the presence of the compatibilizer. This indicates that the two polymers are incompatible but show some extent of compatibility in the presence of a compatibilizer.

3.5 SEM

Figures 10–12 show the phase structures of the HDPE100, HDPE80 and HD80C4 blends, respectively. These SEM micrographs were taken on the cryofractured surfaces (in the longitudinal direction) of the specimens. A pure HDPE

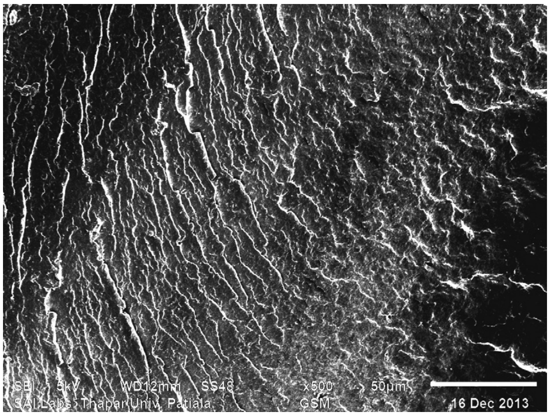

Figure 10 Scanning electron microscopy (SEM) image of 100% high-density polyethylene (HDPE100).

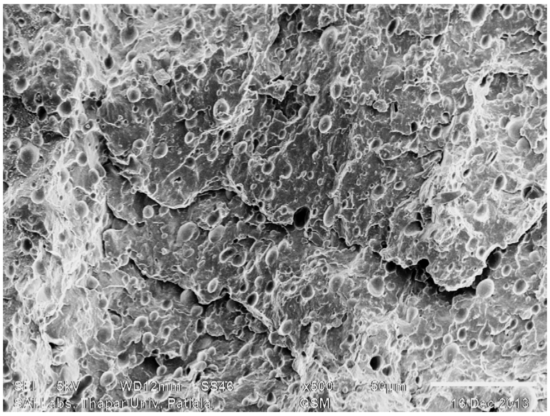

Figure 11 Scanning electron microscopy (SEM) image of 80% high-density polyethylene and 20% poly(L-lactic acid) (HDPE80).

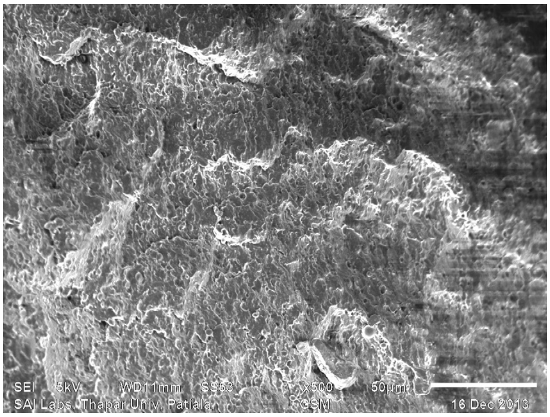

Figure 12 Scanning electron microscopy (SEM) image of 80% high-density polyethylene, 20% poly(L-lactic acid) and 4 phr compatibilizer (HD80C4).

film sample (HDPE100) showed an almost smooth and flat surface, but several pits and potholes were observed on the fracture surfaces of the blends. It is clear from Figures 12 and 13 that the addition of PLLA has prejudiced the morphology of HDPE and introduced roughness in it, primarily because of immiscibility and secondarily due to its brittle nature. Interfacial debonding was seen on the fracture surface of HDPE80 resulting in the generation of the crater-like structures. In contrast, the blend containing 4 phr compatibilizer (HD80C4) exhibited a much finer co-continuous phase structure than without compatibilizer (HDPE80). This fine phase structure of the HD80C4 blend might be the result of improved interfacial adhesion between the two phases and better compatibility because of PE-*g*-MA. Therefore, it might be concluded that PE-*g*-MA has successfully induced some compatibility between the two polymers.

4 Conclusions

HDPE/PLLA polymer blends were made at melting conditions in an extrusion mixer and the films from those blends were prepared in the post-extrusion blown film attachment equipped with the extruder. Amongst all the prepared blends, HDPE80 (without PE-*g*-MA) and HD80C4 (with 4 phr PE-*g*-MA) samples were optimized on the basis of their tensile properties and economic considerations. The blend containing the compatibilizer exhibited better and more interesting mechanical properties. These two blends were further explored for their morphological and some other physical properties. DSC studies revealed that blending PLLA with HDPE produced negligible effects on the melting points of individual polymers, which was due to their immiscibility. However, through blending, heat of fusion HDPE and PLLA decreased, as compared to those of neat polymers, which showed some gain in compatibility. The percent crystallinity of HDPE was decreased in its blends and that of amorphous PLLA having zero crystallinity initially, enhanced considerably when blended with HDPE. A peak-shift of approximately $10\ cm^{-1}$ in the HD80C4 blend (as compared to HDPE80) was observed in the XRD study, which might be due to the hydrogen bonding interaction in the two phases in the presence of PE-*g*-MA. This indicates that the two polymers were incompatible but gained some extent of compatibility in the presence of the compatibilizer. The morphological studies indicated that the compatibilizer influenced the morphology of the HDPE/PLLA blends and is suitable for improving the interfacial adhesion and interaction between HDPE and PLLA.

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