Evaluation of Morphology and Deformation Micromechanisms in Multilayered PP/PS Films: An Electron Microscopy Study

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Summary: Nanostructured polymers and ultra-thin polymer layers are used more and more in technical applications like nanotechnology and microelectronics. Therefore, it is really important to understand the size-scale dependent properties as bulk polymers become thinner and more two-dimensional. Here the morphology as well as the macroscopic and the microscopic deformation behaviour of multilayered films of polypropylene (PP) and polystyrene (PS) have been investigated. For investigation different microscopic techniques and tensile testing were used. The films were prepared by multilayer coextrusion, whereas the composition of PP and PS and the film thickness – and therefore the thickness of each layer – varied. The thinnest calculated thickness of a single layer was about 5 nm. It is shown that the PP/PS films consist usually of homogeneous layers with only few defects. As the composition of PP/PS deviates strongly from 50/50 or the films get thinner the number of defects increases and the layered system turns to irregular lamellar system. In macroscopic tensile tests the small PS layers affect the elongation at break enormously: Most of the samples are brittle. For the films with a composition of PP/PS 90/10 and the film PP/PS 70/30 with a film thickness of 25 μm an elongation at break of 66% and higher could be reached. Transmission electron microscopy on these samples shows that the layers are characterized by plastic yielding in local deformation zones.

Keywords: deformation mechanism; electron microscopy; multilayered films; polymer morphology

Introduction

For development of novel polymeric materials through combination of two or more polymers different strategies are used. One is the multilayer coextrusion. The aim is to get new polymeric materials with the combined properties of the single components or with new, superior properties. The centre of current research is the development of nano- and microstructured materials with specific mechanical and other functional properties. This involves also the design and fabrication of ultrathin and sometimes highly constrained polymer layers. Therefore, it is really important to understand the size-scale dependent properties as bulk polymers become thinner and more two-dimensional.

Because of their incompatibility many polymers are not optionally mixable. With multilayer coextrusion it is possible to combine incompatible polymers like polypropylene (PP) and polystyrene (PS) in such a way that structures down to 10 nm can be created.[1] A summery about processing and application of multilayer coextrusion is given in[2] and[3] gives an overview about the different investigations

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on multilayers. These studies usually refer to composites of two amorphous polymers, whereas two brittle or one brittle and one ductile polymer are combined. The combinations of poly(styrene-acrylonitrile) (SAN) and polycarbonate (PC),[4–6] PC and poly(methylmethacrylate) (PMMA)[7,8] and polystyrene (PS) and PMMA[9] are very well known. Morphology and mechanical properties are examined by optical microscopy (OM), scanning electron microscopy (SEM) and sometimes by atomic force microscopy (AFM). Moreover there are only a few studies on combinations with at least one crystalline polymer.[1,10–12] Investigations of the micromechanical deformation behaviour are done above all with the SAN/PC system. Beside the dependence on the volume fraction of the single polymers an essential influence of layer thickness on the stress-strain behaviour was found.[6]

Examinations on layer forming heterogeneous polymer systems of SBS-block copolymers showed that a reduction of materials dimension from the macro- to the micro- and nanoscale could cause a dramatic change in the deformation mechanisms.[13,14] An open question is if such dramatic changes can also occur in multilayer composites.

The goal of this work is two fold: investigation of structure development, deformation mechanisms and micromechanisms of those structures using direct imaging techniques.

Experimental Part

Materials and Sample Preparation

The starting materials used for preparing multilayered films were polystyrene (PS) and isotactic polypropylene (PP). The layered composites of the samples were produced at Case Western Reserve University (CWRU), Cleveland, Ohio, USA using the well established multilayer coextrusion procedure.[2] The samples described here have PP/PS compositions by volumes of 90/10, 70/30, 50/50, 30/70 and 10/90 and the film thickness of each composition is varied. An overview of the samples studied in this work is presented in Table 1.

Microscopic Techniques

Primarily transmission electron microscopy (TEM, 120 kV, LEO 912, Germany) was used to visualize the structural details in the multilayered composites. Ultra-thin sections (80 nm thick) were ultramicrotomed from a piece of bulk specimen normal to extrusion direction using a diamond knife at room temperature. Prior to the room temperature sectioning for the TEM studies, the bulk specimens were treated with Ruthenium tetroxide (RuO_4) vapour for several hours at 60 °C.

For the study of strain induced structural changes (i.e. the micromechanical properties) of the composites, semi-thin sections (500 nm thick) were cut using a diamond knife parallel to the extrusion direction (see Figure 1) at −120 °C. Thereafter the sections were deformed in a special tensile-device. The strained films were fixed in the strained state and directly studied with a transmission electron microscope (TEM; JEM 4000FX of company JEOL, Japan) operating at an acceleration voltage of 400 kV. Those studies were carried out at Max Planck Institute for Microstructure Physics in Halle (Saale), Germany.

Table 1.
Layer thicknesses of the multilayered films calculated from the relative compositions.

PP/PS 1024 layers	film thickness [μm]	PP layer thickness [nm]	PS layer thickness [nm]
90/10	250	450	50
	125	225	25
	25	45	5
70/30	250	350	150
	125	175	75
	25	35	15
50/50	250	250	250
	125	125	125
	25	25	25
30/70	250	150	350
	125	75	175
	25	15	35
10/90	250	50	450
	125	25	225
	25	5	45

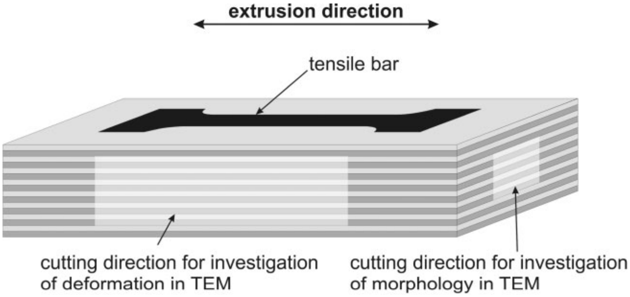

Figure 1.
Scheme showing the ways of preparing tensile test specimens for characterization of mechanical properties, TEM sections for investigation of morphology and TEM sections for investigation of deformation.

Scanning electron microscopy (SEM; JEOL 6300, Japan) was used to gain the overview of the morphology of the multilayered films. The remaining blocks of preparation for TEM were sputter-coated with approximately 10 nm gold film before the SEM examinations. The advantage of the examination of the remaining sectioned block is that a large specimen area can be inspected easily albeit the resolution of SEM is limited compared to TEM.

Mechanical Testing

Tensile testing was performed using a universal tensile machine (Zwick, Ulm, Germany) at room temperature (23 °C) at a cross-head speed of 50 mm/min. The gauge length of the tensile specimens punched out of the extruded sheets with their long axis along the extrusion direction was 50 mm. The specimens were measured using traversal displacement of the cross-heads.

Results and Discussion

Characterization of Multilayered Film Morphologies

In previous studies, various microscopic techniques, scattering methods and differential scanning calorimetry (DSC) were utilized for the investigation of the structure and nanostructure evolution in similar systems (PP/PS,[1] PE/PS[10,11]). This work is primarily aimed at the investigation into the overall morphology and its influence on the deformation micromechanisms. Thus, to begin with, we analyzed the morphology of the extruded films as a function of thickness of individual layers and relative composition of the components. For this purpose, the samples were treated with RuO_4 and subsequently sectioned at room temperature via ultramicrotomy to prepare ultra-thin sections for the TEM. The remaining blocks of the samples were imaged by SEM. The results are presented in Figures 2 and 3.

Figure 2 shows the SEM micrographs of multilayered PP/PS films having identical thickness (250 μm) but differing in the relative homopolymer compositions. To understand the contrast of Figure 2 one should first have a look at a TEM micrograph as given in Figure 3. As one can see the interphase between the PP and PS layers is almost black whereas the layers themselves are grey. That means that the preferential deposition of the RuO_4, which diffuses into the less dense packed areas, is in the interphase. This observation is independent of the PP/PS compositions (see Figure 4) and arises from the fact that the interfacial region in the multilayered PP/PS films is loosely bound - a typical feature of strongly incompatible system. Doing SEM on a flat surface reveals contrast between materials with a high difference in atomic weight. Materials with light atoms like carbon (C) in PP and PS appear dark and materials with heavy atoms like ruthenium (Ru) appear bright in the secondary electron image. The advantage of this unusual preparation

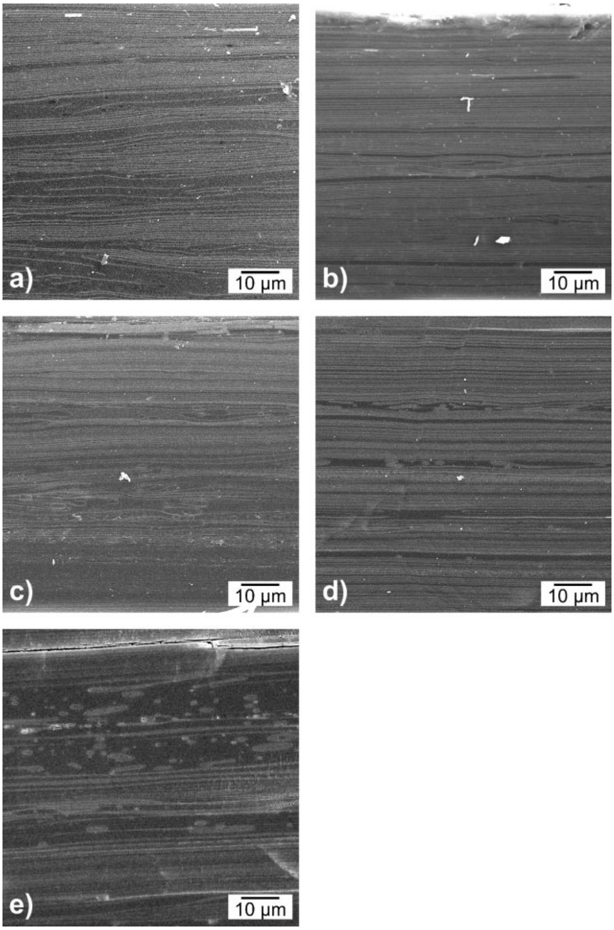

Figure 2.
SEM micrographs of stained multilayered PP/PS films, each 250 μm thick, of varying compositions: a) PP/PS 90/10, b) PP/PS 70/30, c) PP/PS 50/50, d) PP/PS 30/70, e) PP/PS 10/90.

technique for SEM is that a large area can be inspected in a short time. The bigger the estimated area the better one can find out the representative structure of the whole sample.

In the TEM one can only image small areas and therefore there is the risk that one does not image the typical structure. The multilayered films have areas with perfect layers and beside them there are regions with plenty of defects. So that it is easy to deduce a false conclusion. Going from top to bottom of Figure 2 the bright lines seen on the SEM micrographs are only the interphase between the PP and PS layers, the layers themselves are dark. In Figures 2a and 2e the thin PP and PS layers respectively (calculated thickness 50 nm) can not be resolved. So here the bright lines are the PP and accordingly PS layers plus the interphase.

The inspection of the SEM images reveals that the multilayered films consist primarily of continuous layers of constituent polymers, the layers being more or less uniform in thickness across the film thickness of each sample. In between these excellent layers there are some local areas with a concentration of layer defects like rupture of layers, combining of layers, ending of layers and forming a drop shaped end. The films with a composition of PP/PS

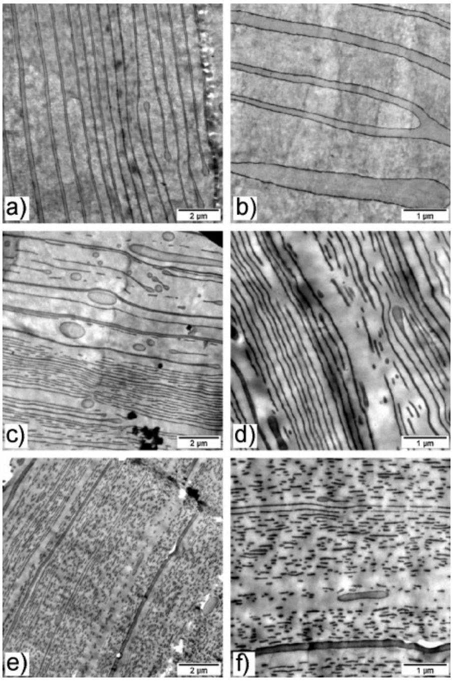

Figure 3.
Lower (left) and higher (right) magnifications of TEM micrographs of PP/PS 90/10 films having variable film thickness: a+b) film thickness 250 μm, c+d) film thickness 125 μm, e+f) film thickness 25 μm.

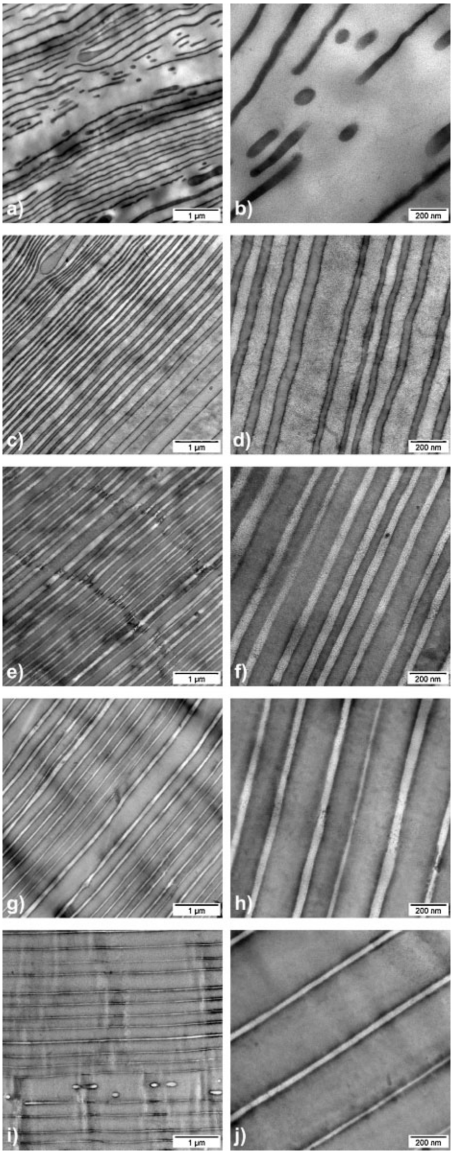

Figure 4.
Lower (left) and higher (right) magnifications of TEM micrographs of PP/PS films having variable PP/PS compositions, the film thickness was approximately 125 μm: a+b) PP/PS 90/10, c+d) PP/PS 70/30, e+f) PP/PS 50/50, g+h) PP/PS 30/70, i+j) PP/PS 10/90.

90/10 and 10/90 have more defects than the other three films. Additionally to the already depicted defects one can find a lot of drops formed from layer rupture of the minority phase.

The detailed morphologies of the multilayered samples were investigated by TEM. Let us begin the discussion of the film morphology with a sample having highly asymmetric composition: PP/PS 90/10 samples having variable film thicknesses. In Figure 3 TEM micrographs of the PP/PS 90/10 samples with film thicknesses of 250 μm, 125 μm and 25 μm are presented. The dimensions of the PP and PS laminates are indexed in Table 1. Owing to constant relative composition and variable thickness of the films, one would expect decrease in the thickness of individual layers with decreasing total film thickness.

In the TEM micrographs the PP and PS layers are grey, the interphase between the layers is almost black. Due to stronger staining by RuO_4, the polystyrene phase appears darker than the PP phase. The areas occupied by the darker (PS) and less dark (PP) regions correspond roughly to PP/PS volume composition adjusted during processing of the films by multilayer coextrusion. For the 250 μm thick film (Figures 3a+b) the estimated thicknesses of the PP and PS layers are 450 nm and 50 nm (see Table 1). The experimentally measured thickness of the layers is however a little bit higher in this sample. There are some PP layers which are even thicker than 1.5 μm (see Table 2). The layers are mostly continuous.

Decreasing the film thickness to 125 μm (adjusting the estimated thickness of PP and PS layers to 225 nm and 25 nm, respectively), the two characteristic features become apparent. First, the minority component that is supposed to build the layers 25 nm in thickness, break up forming elongated PS domains embedded in the PP layers. Secondly, the uniformity in the thickness of the layers also begins to vanish (see Figures 3c+d). As a consequence, the experimentally measured layer thickness shows much higher deviation from the estimated value (see Tables 1+2). The film shows a wide distribution of the laminates of the individual polymers in this sample.

The morphology of the film changes dramatically when the thickness of the film is further decreased to 25 μm. The morphology of the film comprises the domains of polystyrene embedded in polypropylene matrix. In this case multilayer morphology of the film is almost destroyed (Figures 3e+f).

Figure 3 made it clear that with decreasing film thickness at constant composition the layers become more and more discontinuous. Moreover, the experimentally measured thicknesses of the layers deviate strongly from the targeted value (see Table 2).

By changing the relative volume fraction of the starting polymers the relative thickness of the polymers in the multilayered films can be adjusted. Thus, to study the effect of composition on the evolution of multilayered morphology, the PP/PS films of variable compositions (PP/PS volume fractions of 90/10, 70/30, 50/50, 30/70 and 10/90) were studied keeping the total thickness of the films constant (see the TEM micrographs in Figure 4). The thicknesses of the individual layers are indexed in Table 1.

This is not the objective of this paper to discuss the crystalline structure of PP phase in the multilayered systems. However, it is to be noted that, for the films containing PP as major component (for instance, see Figures 4a-d) the lamellae structures predominantly correspond to the α-crystalline form of isotactic polypropylene. If the thickness of the PP layers is too small (approximately 200 nm or less such as for samples having 50% or less PP), the cross-hatched lamellar morphology of the α-form of polypropylene is disturbed. The lamellae have no preferential alignment relative to the adjacent layers. In the TEM micrographs, the continuous layers of polypropylene and polystyrene are prevalent which also reflect the composition of the multilayered films. As expected, if the composition is extremely asymmetric (for example, for 90/10 or 10/90 compositions), thin layers of the minority component exist in the vicinity of the much thicker adjacent layers of the major component.

The targeted thickness of the minority polymer component in the films for the most asymmetric composition of PP/PS 90/10 or PP/PS 10/90 (film thickness 125 μm) was

Table 2.
Calculated and measured layer thickness of the PP/PS 90/10 films in the considering TEM micrographs using image processing software.

	Film thickness (μm)	Thickness of PP layers (μm)		Thickness of PS layers (μm)	
		Calculated	Measured	Calculated	Measured
PP/PS 90/10 1024 layers	250	450	505 > 1500 in parts	50	82
	125	225	130	25	48
	25	45	—	5	—

25 nm (see Table 1). For these compositions, it was difficult to achieve the uniform and continuous layers of the polymers side by side. This difficulty was more pronounced when polypropylene served as majority component (see Figures 4a+i). Nevertheless, the continuity as well as the uniformity of the layers was much better than in the case when the targeted thickness was 5 nm (film thickness 25 μm) (see Figures 3e+f). Thus, it can be concluded that the formation of uniform and continuous layers of the polymers is strongly affected by the asymmetric composition of the laminated films.

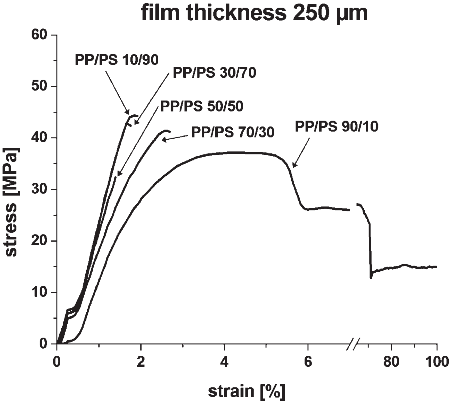

Figure 5.
Tensile stress-strain curves of multilayered PP/PS films, the film thickness is 250 μm while the PP/PS composition changes.

Characterization of Mechanical and Micromechanical Properties

In this section, the correlation between the observed morphology and the deformation micromechanisms will be described.

Table 3 gives the characterization of the mechanical behaviour of the PP/PS films dependent on the composition and the calculated PS layer thickness. In Figure 5 the tensile stress-strain curves of the samples with 250 μm film thickness are presented, Figure 5 showing primarily the effect of composition, while Figure 6 exhibiting the effect of film thickness on the compositions PP/PS 90/10 and 70/30.

The investigated PP/PS samples with the compositions PP/PS 10/90, 30/70, 50/50 are brittle, whereas the PP/PS 90/10 samples are ductile. The films with the composition PP/PS 70/30 reveal an intermediate behaviour. When the film thickness is 125 μm or more the samples are brittle but if the film thickness decreases to 25 μm it gets ductile. For all films it can be noticed that with decreasing film thickness – and therefore thickness of a single layer – at constant composition there is a trend to increase the elongation at break, for the compositions PP/PS 70/30 and 90/10 it is a clear fact (Figure 5 and Table 3).

Table 3.
Mechanical characterization of the PP/PS films dependent on the composition and calculated PS layer thickness studied in this work.

PP/PS	film thickness [μm]	calculated PS layer thickness [nm]	average Young's modulus [MPa]	average yield stress [MPa]	average elongation at break [%]
90/10	250	50	2053	37	66
	125	25	2031	39	95
	25	5	1993	37	271
70/30	250	150	2119	41	2,4
	125	75	2333	42	2,5
	25	15	2018	44	82
50/50	250	250	2726	42	1,4
	125	125	2753	45	2,2
	25	25	3207	52	3,9
30/70	250	350	3069	39	1,7
	125	175	2866	42	2,1
	25	35	3326	66	2,7
10/90	250	450	3433	42	1,7
	125	225	2931	40	1,9
	25	45	3712	80	3,6

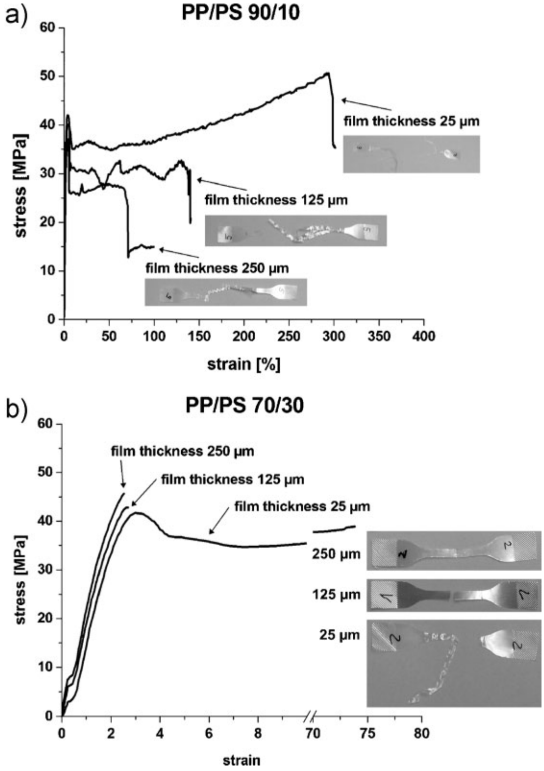

Figure 6.

Tensile stress-strain curves of multilayered PP/PS films having different film thickness: a) PP/PS 90/10, b) PP/PS 70/30.

In the two samples PP/PS 50/50 25 µm film thickness and PP/PS 90/10 125 µm film thickness the calculated layer thickness of PS is 25 nm, the layer thickness of PP is 25 nm and 225 nm respectively. As can be seen in Table 3 the elongation at break is quite different – about 4% for the 50/50 composition and 95% for the 90/10 composition. This reveals that the ductility of the films is not only influenced through the film thickness and layer thickness respectively but also through the composition.

As discussed above, morphology of the multilayered films is influenced by the composition and film thickness, too. Hence, the high elongation at break of the PP/PS 90/10 with 25 µm film thickness can be explained through the morphology, which is more a particle filled PP than a multilayered system. The high deformation of the thicker films with PP/PS 90/10 and the PP/PS 70/30 film thickness 25 µm can not be explained by morphology – here we have layered films.

Interesting results are observed in Figure 6a in which the stress-strain curves of PP/PS 90/10 films are presented. The yield stress and Young's modulus of the samples remain almost constant (see Table 3). It can be noticed that the average elongation at break for 250 µm thick sample is about 66%. Recall that this sample has rather uniform alternating PP and PS layers having measured thicknesses of approximately 500 nm and 80 nm. If the film thickness is decreased to 125 µm (and thus leading the PP and PS layer thickness to 130 nm and 50 nm, respectively), the elongation at break increases from 66% to 115% (see also Table 3). If one further reduces the film thickness to 25 µm (leading to nominal PP and PS layer thickness of 45 nm and 5 nm, respectively), the elongation at break again increases to 271%. It should be, however, kept in mind that in the last case, the film showed the morphology that is typical of a nanostructured blend rather than that of an ideal multilayered film. Nevertheless, there is a clear tendency of increasing overall stretchability of the films with decreasing layer thickness of the component polymers.

The strong influence of layer thickness on the mechanical properties of the multilayered films could be observed in PP/PS 70/30 composite films in which the PS layers had nominal thicknesses of 150 nm, 75 nm and 15 nm for the films having thickness of 250 μm, 125 μm and 25 μm, respectively. The stress-strain curves of those films are presented in Figure 6b. A dramatic increase in strain at break was observed for the sample having PS layer thickness of 15 nm. Unlike the PP/PS 90/10 sample having 25 μm film thickness, which has the morphology comprising PS domains embedded in PP matrix, all the PP/PS 70/30 samples showed remarkably well ordered multilayered morphology (see Figures 2 and 4). Thus, it can be concluded that the thickness of the PS layers plays a decisive role in the determination of mechanical properties of the multilayered composites.

The detailed studies on the micromechanical behaviour of the composites were conducted by means of comparatively high voltage transmission electron microscopy (TEM, 400 kV). The strained semi-thin sections were directly transferred to the specimen holder of the TEM without chemical treatment which are usually carried out during TEM investigations of polymers. The investigation of micromechanical behaviour we did on the PP/PS 90/10 sample with a film thickness of 250 μm. This sample has a layered morphology with only few defects and in the tensile tests a high elongation at break could be seen. The other reason why to take this sample is that it is easier to prepare than thinner samples.

Figure 7 shows TEM micrographs of the PP/PS 90/10 sample with a film thickness of 250 μm. The calculated thickness of PS is 50 nm. In the macroscopic tensile tests an average elongation at break of 66% can be reached, for a single specimen it can be 100% (see Table 3 and Figure 6). For this it is interesting to see what happens in the sample and in the single layers during drawing – especially in the PS layers. The micrographs show different areas on the strained samples: There are domains with almost no elongation (dark) and beside this there are domains with extreme high elongation (bright). In the areas with the high elongation delamination into different stacks of layers takes place. In contrast no delamination could be found in the unstrained areas. Cavitation on layer defects (e.g. PS particles or ending of PS layers) occurs in both the high strained and not strained domains through sample preparation. The cavities are elongated by straining the semi-thin sections, see Figure 7b).

In Figure 8a, which is a higher magnification of Figure 7 (sample PP/PS 90/10, film thickness 250 μm) the darker almost non-strained areas are named 'undeformed' whereas the brighter high strained

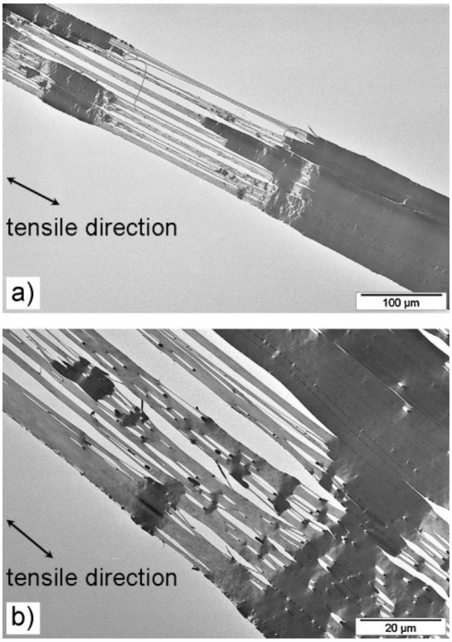

Figure 7.
TEM micrograph of deformation of the multilayer film PP/PS 90/10 with 250 μm film thickness at a) lower and b) higher magnification.

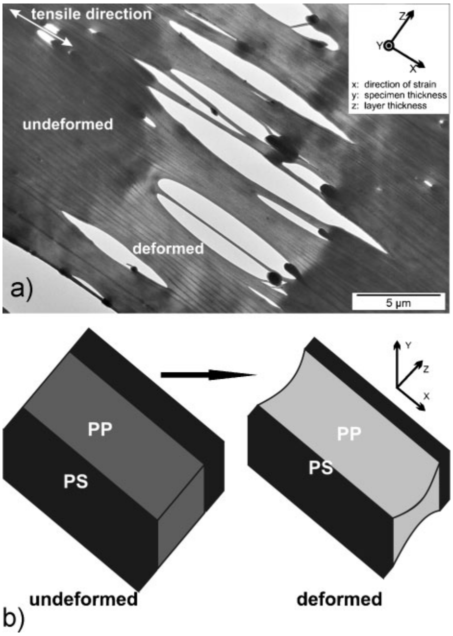

Figure 8.
Deformation of PP/PS 90/10 with 250 μm film thickness: a) TEM micrograph, b) model of deformation.

domains are signified as ‘deformed’. In the deformed regions delamination takes place at the interphase between the PP and PS layers. Cavitation can be seen at defects in layers. These cavities are extended during straining. Beside these effects a really important and new effect can be seen: There are homogeneous deformed polystyrene layers in the highly deformed areas.

Another thing what can be seen in Figure 8a is that the contrast changes between the deformed and undeformed regions. In the non-strained areas both polymers are dark. It is difficult to differentiate the layers of polypropylene and polystyrene from each other. In contrast in the deformed areas PP appears bright and PS dark (nearly as dark as in the undeformed region).

In transmission electron microscopy contrast can be generated through mass absorption contrast that means if there is a difference in density or thickness of the sample. In this case there is nearly no difference in density of PP and PS because both polymers are built up of carbon and hydrogen so that the density is nearly the same. Moreover the polymers are not stained. After sectioning the sample was overall 500 nm thick. That means that we have differences in thickness only from straining the sample. This leads to the model given in Figure 8b. In the undeformed region both polymers are dark. Polypropylene gets brighter in the deformed area, so it has to be thinner in the strained state than in the non-strained state. Polystyrene in the deformed area is as dark as PS in the undeformed area. That means that it is equal in thickness (specimen thickness, in y-direction) in the deformed as well as in the undeformed area.

To understand the deformation of the given sample we introduce a coordinate system (see Figure 8b): x is the direction of strain, y is the specimen thickness (which is 500 nm after sectioning), z is the direction of sample thickness or layer thickness. The effects described above are in the y direction – PP gets thinner after straining and the thickness of PS is equal before and after straining. Therefore, polystyrene can be highly deformed (as shown in Figures 7 and 8) only by decrease in the layer thickness of PS in the z direction. The results are given in Table 4. Here it could be found that the thickness of PP is nearly the same in the undeformed and deformed region (alteration only from 218 nm to

Table 4.
Measured layer thicknesses in z-direction of the deformed and undeformed areas of the PP/PS 90/10, film thickness 250 μm (measured on Figure 8a).

		Measured thickness of a single PP layer (nm)	Measured thickness of a single PS layer (nm)
PP/PS 90/10 1024 layers	undeformed area	218	78
film thickness 250 μm	deformed area	196	54

196 nm). But the layer thickness of PS is clearly decreasing (78 nm in the undeformed state and 54 nm in the deformed state). So we can summarize that the alteration in the thickness of the layers is oppositional in the y and z direction.

From Figure 8 and Table 4 we can give the following conclusion: The multilayered PP/PS film can be deformed whereas PP and PS layers can be obtained but delamination occurs, too. In this sample polystyrene is clearly higher deformed than the well-known 3% for bulk-PS. The thin layer yielding effect of PS in the x and z direction could be verified by experimental data.

The results of direction dependent reduction of layer thickness can be explained like this: In literature it is described that brittle polymers can be homogeneously deformed if the thickness is under a critical level. Kausch und Michler believe that this critical level is two-times the entanglement mesh size.[15] For PS the entanglement mesh size is 15 nm, so the critical level is 30 nm. 80 nm in the z direction is only two-to-three-times higher. 500 nm (in the y direction) are two much for yielding. PP is constrained between the PS layers, so that its yielding in the z direction is hindered, whereas the yielding in y direction is free.

Conclusion

The morphology and deformation behaviour of the multilayered PP/PS films produced by coextrusion technique have been evaluated by means of electron microscopy. The macroscopic behaviour of the films was determined by uniaxial tensile testing. The findings of this work can be summarized as follows.

- It was possible to produce the multilayered films comprising alternating and continuous layers of PP and PS having uniform thickness. The relative composition of the polymers could be varied over a wide range enabling the formation of layers having thickness down up to 25 nm.
- The continuity and uniformity of the layers was strongly affected by the film thickness and asymmetric composition. The thinner the film or more asymmetric the composition, the higher was the trend to form discontinuous and non-uniform laminates.
- The mechanical and micromechanical properties of the individual components were affected by the thickness of the PS layers. The lower the thickness of the PS laminates, the higher was the observed ductility of the films at constant yield strength. Strong effects of layer thickness on elongation at break could be observed at the compositions of PP/PS 70/30 and PP/PS 90/10.
- The composition has high influence on the ductility of the multilayered films, too.
- The deformation of the multilayered films was found to be of local nature. High degree of plastic yielding was observed in the PP/PS 90/10 sample with 250 μm film thickness. The PS layers had a measured thickness of 80 nm. This high ductility of thin PS layers can be compared with the "thin layer yielding effect", found in thin PS layers in SBS blockcopolymers.
- It was found that the deformation of the PP and PS layers in the multilayered sample depends on the direction. By drawing the sample in layer direction (x direction) the PP layers are reduced in y direction whereas the PS layers are reduced in z direction.

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