Experimental Investigation of the Development of Interfacial Instabilities in Two Layer Coextrusion Dies

The stability of two-layer flow of polyethylene and polystyrene is experimentally studied in different flow geometries and for various flow rate ratios. A first coextrusion device allows to stop the coextrusion flow in a very long slit channel, to cool down the polymer sample and to dismantle the die in order to extract extrudate which is then carefully analyzed.

A second device allows to observe the whole slit flow through transparent lateral walls and to record the interfacial waves in both spontaneous and controlled unstable conditions.

Both devices point clearly out that the interfacial defect begins to grow after a specific flow distance and is then quickly amplified. This demonstrates the convective character of interfacial wave. Controlled unstable processing conditions in transparent die allow to measure accurately growth rate of defect in the linear regime and show quick occurrence of non linear regime.

1 Introduction

This paper is concerned with the experimental study of the shear flow stability of a multilayer incompatible polymer system constituted of molten low density polyethylene and polystyrene. Interfacial instability of molten polymers has received in the past ten years increasing attention due to the increasing use of coextrusion technologies to manufacture products combining the mechanical, optical or barrier properties of the different polymers. Coextrusion is widely used for example in food packaging where different polymers are separately melted in screw extruders and then flow simultaneously in the extrusion die. For some processing conditions wavy interfaces between the different polymer layers, due to a flow instability of the system in the die, are observed on the final product. These disturbances of the thickness regularity of each layer are undesirable and can limit both production rates and mechanical or optical properties of final products.

From a theoretical point of view, the occurrence of such instabilities has been largely analyzed by looking at the temporal stability of the plane Poiseuille flow, principally for the two layers case. Linear temporal stability is computed by studying the growth or decay with time of spatially periodic infinitesimal perturbations. Important contributions for viscoelastic fluids can be found in references [1 to 5]. This instability occurs at very low Reynolds number and it is now accepted that important control parameters are the viscosity ratio, elasticity ratio and layer thickness ratio (or flow rate ratio). Other factors such as density stratification or surface tension are also considered.

Despite the large industrial relevance of this subject, there are few experimental studies concerning coextrusion instabilities for commercial polymers or more generally for fluids with significant viscosity and elasticity. Han and Shetty [6 to 8], Antukar et al. [9] have published experimental results in industrial configurations. For example in [8] stable and unstable coextrusion conditions are identified and related to the thickness ratio and the viscosity and first normal stress difference ratios at the interface. Very comprehensive experiments on the stability of two-layers channel flow have been made by Khomami and coworkers. A polypropylene/polyethylene flow was studied in [10 to 13] whereas [14] was concerned with model fluid systems such as silicone oil/propylene glycol, silicone oil/polybutene-kerosene or silicone oil/Boger fluid.

In experiments [10 to 13], periodic flow rate oscillations of small amplitude at die entry were generated. Evolution of the interface deviation along the die was observed through four optical windows for various wavenumbers of the interface defect and various layer thickness ratios (or flow rate ratios). Authors show that perturbations grow or decay as they travel downstream pointing out clearly the convective nature of the interfacial instability.

More recently, Valette et al. [15] have investigated the interface stability of a polyethylene/polystyrene (or PE/PS) coextrusion flow. They tried to link processing parameters (such as temperature, flow rate ratios, ...) with film features observed at die exit. These experiments were performed both in industrial and laboratory conditions in order to point out the general behaviour of such stable/unstable transitions. This transition is observed by increasing polyethylene flow rates or by decreasing temperature.
In the present paper, we study more precisely the spatial development of interfacial instability for the same PE/PS system in two laboratory devices. We want to check the main features of this probable convective instability inside the die in order to have a better understanding of quality of extrudates obtained at die exit.

Experimental results reported in this paper were obtained using two different extrusion devices. The first one (device 1) is a slit die which can be rapidly closed at the entrance and exit and then dismantled after cooling. The extracted solidified samples can then be cut to observe the spatial development of interface defects along the flow path for various coextrusion conditions. The second apparatus (device 2) is a slit die with totally transparent walls. The main difference with [10] is that our apparatus has a bigger width aspect ratio (100:1 or 50:1 instead of 10:1) and can provide an entire picture of the spatial wave (a large transparent glass instead of 6 windows). A CCD camera allows to observe the development of interface defects for random or temporally regular disturbances. The rheology of the two polymers and the two experimental setups are presented in the next sections.

2 Materials

A low density polyethylene (1003 FE 23 from AtoFina) and a polystyrene (1240 from AtoFina), have been used. Dynamic rheology measurements were performed on a parallel plate rheometer at different temperatures. Figs. 1 and 2 show the master curves of the complex modulus obtained at 180°C for, respectively, the polyethylene and the polystyrene. By assuming the Cox-Merz rule, viscosity $\eta$ (Fig. 3A) and relaxation time $\lambda = \eta''/G''$ (Fig. 3B) are deduced. When fitting the $\eta(\dot{\gamma})$ and $\lambda(\dot{\gamma})$ curves to a Carreau-Yasuda model one obtains the White-Metzner constitutive equation, which was used in [15] to describe the behaviour of polystyrene and polyethylene.

It is interesting to notice that polyethylene presents a Newtonian plateau at low shear rate whereas polystyrene is markedly shear rate dependent in the same range. This results in a shear rate (i.e. flow rate) dependent viscosity ratio between the two polymers. At low shear rate polystyrene is more elastic than polyethylene and the reverse situation is encountered at high shear rate.

As a consequence, it is difficult to claim that one layer is more viscous (or elastic) than the other one : the shear rate is not constant throughout thickness and a relevant parameter is
rather the ratio between the viscosity or elasticity estimated at the interface. But the velocity profile has to be known before computing such ratios. This is a marked difference with previous experiments of Khomami et al. [10] made with high density polyethylene (HDPE) and polypropylene (PP). The HDPE is ten times less viscous and ten times less elastic than the PP and so the PP layer is always more viscous and more elastic than the HDPE.

As in our previous study [15], it was shown that interfacial waves are observed more frequently at relatively low temperatures, temperature was fixed to 180°C in the sequel.

3 First Device: Solidified Core Extraction

To observe the development of the two-layer interfacial instability, we have first used a slit die allowing relatively easy extraction of the solidified polymer sample. However the design does not correspond to realistic coextrusion conditions: thickness and length are large compared to industrial flat dies dimensions and flow cannot be identified to a two-layer Poiseuille flow. The die length is extensive enough in order to be able to observe precisely the development of the defect along the flow path and the die gap is sufficiently large to avoid too large pressure values. Moreover, a large thickness of the die ensures that in unstable operating conditions the smaller layer is not damaged during dismantling. Therefore, very nice samples are obtained allowing to describe qualitatively spatial growth of interfacial waves. Furthermore, with a small width aspect ratio, there is only one wave in the spanwise direction and the experiments are easier to analyze. Note that this device has been originally built for studying encapsulation in coextrusion flows [16].

3.1 Apparatus

Polymers are melted and pressurized in two Collin screw extruders with a screw diameter of 30 mm and a maximum flow rate of 200 g/min. The die (Fig. 4A) has a length of 600 mm, a width of 54 mm and a depth of 13.5 mm resulting in aspect ratios 44.5 : 1 and 4 : 1. It is composed of four independent pieces that can be taken apart. The temperature of each part of the setup is individually controlled and maintained at 180 °C.

Two guillotines (see Fig. 4B) located on the multi manifold feed-block and at die exit allow to confine molten polymers in the die within a very short period of time.

An oil cooling circuit added to the die allows a rapid cooling. The key point is to be sure that the solidified sample extracted from the die is representative of the situation encountered during the coextrusion process.

3.2 Procedure

Stable and unstable conditions were determined by observation of the extrudate. Flow rate of polyethylene and polystyrene were changed until instability onset was observed. After the coextrusion system had reached a steady regime, screw rotation of both extruders was stopped, the two guillotines were closed and the cooling circuit activated. After ten minutes the die was dismantled and the solidified core extracted. As the polyethylene was colored in red and the polystyrene was transparent, the samples interface could be carefully analyzed. Three processing conditions called (a), (b) and (c) respectively stable, unstable and very unstable are presented.

3.3 Stable Structure (a)

Polyethylene and polystyrene flow rates were $Q_{PE} = 110$ g/min and $Q_{PS} = 47$ g/min resulting in a flow rate ratio $q = Q_{PE}/Q_{PS} = 2.34$. A photograph of the extrudate (from the polystyrene layer side) during stabilized coextrusion conditions is presented on Fig. 5A. The interface is stable even though encapsulation of polyethylene by polystyrene is observed. A
photograph of solidified sample (from the polystyrene layer side) is presented on Fig. 6, right. Interfacial stability is confirmed by Fig. 6, left which presents the longitudinal section of the extrudate sample (cut along the symmetry axis). The interface between the two polymers is flat after the classical development of the Poiseuille two-layer flow and no instability is detected along the whole sample.

3.4 Unstable Structure (b)

Polyethylene and polystyrene flow rates are $Q_{PE} = 112 \text{ g/min}$ and $Q_{PS} = 35 \text{ g/min}$ resulting in a flow rate ratio $q = Q_{PE}/Q_{PS} = 3.20$. A wavy V-shape instability is clearly observed on the photograph of the extrudate presented on Fig. 5B. It is also observed on extracted solidified sample (Fig. 7, right) that this V-shape defect appears close to the die exit at 525 mm from the die entrance. It is first located at the center of the sample and progressively invades the whole width. Growth of the defect amplitude in the flow direction is observed on Fig. 7, left presenting a photograph of the sample cut along the symmetry axis with a scaling factor of 5 in the thickness direction. Even appearing close to the die exit, the interface defect develops very rapidly.

3.5 Very Unstable Structure (c)

Polyethylene and polystyrene flow rates are $Q_{PE} = 136 \text{ g/min}$ and $Q_{PS} = 35 \text{ g/min}$ resulting in a flow rate ratio $q = Q_{PE}/Q_{PS} = 3.89$. A severe wavy V-shape instability is observed on the photograph of the extrudate presented in Fig. 5C. On extracted solidified sample the V-shape defects appear in the middle of the sample at 330 mm from the die entrance and invade rapidly the whole width (Fig. 8, right). Fig. 8, left presents a photograph of longitudinal section of the cut sample with a scaling factor of 5 in the thickness direction. It shows that the interface defect amplitude increases first rapidly, and then the top of the waves are stretched in the flow direction leading at die exit to a superposition of several layers.

3.6 Preliminary Conclusion

Although the basic flow is not exactly the two-layer Poiseuille flow, the flow rate ratio $q$ controls the transition from stable to unstable sheet. Moreover, one can assume that the waves observed at the interface after freezing correspond to the interfacial waves during the process.

These first experiments show the complexity of the spatial development of interface defects. According to flow conditions, very small perturbations of the flow rates (related probably to extruders) either remain not visible (structure (a)) or are significantly increased as flowing downstream (structure (b) and (c)).

The defect becomes clearly visible after a specific length and the nonlinear regime is rapidly reached. It is first located at the center of the die and progressively invades the whole die width. It first exhibits a spatial periodicity, but then the waves are stretched in streamwise direction which induces the development of complex inter-penetrated flow patterns. This points out that there is a need for a more precise study of the de-

Fig. 6. Upper view ($x$–$z$ plane, polystyrene layer side) of the solidified sample for case (a) (right). Side view ($x$–$y$ plane) with a 5 scaling factor in the transverse direction (left)

Fig. 7. Upper view ($x$–$z$ plane, polystyrene layer side) of the solidified sample for case (b) (right). Side view ($x$–$y$ plane) with a 5 scaling factor in the transverse direction (left)
development of the defect in the flow direction. A transparent die is used in the following section to observe the wave development. Furthermore the stable/unstable transition is precisely identified by generating at die entrance a defect of small but visible amplitude.

4 Second Device: Transparent Die and Flow Rate Perturbation Setup

4.1 The Experimental Device

The experimental setup (Fig. 9) consists in a Kaufmann extruder (diameter 40 mm) and a Haake-Rheocord extruder (diameter 20 mm) used respectively for polyethylene and polystyrene.

The two polymers are coextruded into a two-manifold die at a temperature of 180 °C. The final part of the die is a rectangular channel (length of 40 mm, width of 100 mm and thickness of 1 mm) with lateral transparent walls and has a relatively large aspect ratios of 100:1 and 40:1.

Polystyrene is colored in black in order to observe the interface between the two polymers through the side windows. The die is lighted on one side and a CCD camera (resolution 760 x 570 pixels, 24 frames per second) records the interface shape on the other side. The camera is fixed on a micrometric plate enabling an accurate translation in the longitudinal direction of the die. A macroscopic lens is fixed on the camera. At low magnification, one observes the flow in a region corresponding to half of the channel length (20 mm). At high magnification, one observes a channel length of 6.33 mm and interface position may be located accurately (120 pixels correspond to 1 mm). Sequences are recorded by mean of a U-matic video-recorder. Each picture frame is a jpeg file converted in a two-dimensions table containing the gray level of pixels. It is then possible to plot the interface position h(t, x) as a function of time t and longitudinal position x.

4.2 Spontaneous unstable case

The ability of this device to analyze spatial and temporal behaviour of interface for a spontaneously unstable case corresponding to very unstable flow conditions is illustrated in figures 10 to 12. Polyethylene and polystyrene flow rates are Q_{PE} = 58 g/min and Q_{PS} = 5.8 g/min which results in a flow rate ratio q = Q_{PE}/Q_{PS} ~ 10.

Fig. 8. Upper view (x–z plane, polystyrene layer side) of the solidified sample for case (c) (right). Side view (x–y plane) with a 5 scaling factor in the transverse direction (left)

Fig. 9. Device 2: sketch of coextrusion and observation systems
The extrudate is very perturbed as seen in Fig. 10. Note that, as polystyrene is colored in black, the gray intensity is a function of the polystyrene layer thickness. Despite the chaotic aspect of the extrudate it is possible to estimate a spatial periodicity of the defect. Note also that the encapsulation is negligible and pattern modification shown on both extrudate sides is only due to adhesive conditions at the walls.

Fig. 11 shows a sequence of pictures through transparent walls in the die end part (in the range $32 \, mm \leq x \leq 40 \, mm$) at time interval of 0.08 s. This points clearly out that the thickness of the polystyrene layer is strongly perturbed. Some of the random small perturbations (induced by the screw extruders) and which are not visible in the entrance region of the channel, are advected and largely amplified in downstream region. For example, a defect appearing at position $x = 32 \, mm$ and time $t = 0$ is advected and reaches the die exit at time $t = 0.96 \, s$. So the perturbation has an apparent velocity of $\sim 8 \, mm/s$ (note that the mean velocity of the flow is $\sim 7 \, mm/s$).

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**Fig. 10.** Photograph in $x$–$z$ plane of extrudate obtained at $180^\circ C$, for $Q_{PB} = 58.2 \, g/min$ and $Q_{PS} = 5.8 \, g/min$

**Fig. 11.** Optical sequence observed in $x$–$y$ plane near the die exit ($32 \, mm \leq x \leq 40 \, mm$) of a spontaneously unstable flow, time interval between each shot is 0.08 s. Die edges are drawn on each photograph. Polystyrene is located in dark upper side.
Figs. 12A and B show diagrams h(t) in the range \(0 \leq t \leq 15\) s obtained by image analysis for the same processing condition at, respectively, position \(x = 5\) mm (close to die entrance) and \(x = 35\) mm (close to die exit). The picture sequences in Fig. 11 and diagrams in Fig. 12 point clearly out the convective nature of the interface instability. The interface looks flat at die entrance whereas numerous very small interface defects, not visible at the channel entrance, are drastically amplified as flowing to die exit. All these defects are randomly generated (probably by screw extruders) and amplified simultaneously and then do not exhibit a regular two-dimensional shape in the transverse direction (see Fig. 10). Then, a superposition of different waves is recorded through the glass and it is not possible to perform a temporal analysis of the defect even though a spatial periodicity can be estimated on the extrudate.

In the following section, the onset of the instability is more precisely studied by introducing small but visible and controlled flow rate perturbations which allow to analyze slightly unstable processing conditions.

4.3 The Periodic Forcing Experiments

Periodic flow rate perturbations are obtained by modifying the Kaufmann screw rotation speed. The voltage generator driving the screw velocity is perturbed by a sinus function at a given frequency \(N\) in the range \(0.2\) Hz \(\leq N \leq 2\) Hz. These controlled perturbations of relatively large amplitude do not interfere in slightly unstable conditions with spontaneous perturbations (of smaller amplitude) previously described. This ensures that the interface defect is two-dimensional (homogeneous throughout the width of the die).

The sinus function for the perturbed rotation velocity was adjusted in order to obtain a pressure oscillation amplitude at the die entrance equal to 2% of the initial pressure. This value is small enough to keep the flow rates constant. The die thickness had been increased to 2 mm (the two aspect ratios are now \(5:1\) and \(20:1\)) in order to ensure better accuracy of interface measurements. Polyethylene and polystyrene flow rates are \(Q_{PE} = 87.4\) g/min and \(Q_{PS} = 7.4\) g/min (\(q \sim 12\)) and temperature remains set to 180°C. The flow rate ratio is higher than in the previous experiment which was considered as very unstable but the die gap is higher (2 mm instead of 1 mm) which explains that one deals with slightly unstable conditions.

For these operating conditions, no interface fluctuations are found on the extrudate or within the die in steady operating conditions because intrinsic perturbations of the system are not sufficiently amplified to be detectable (instabilities are observed in [15] by slightly increasing the flow rate ratio \(Q_{PE}/Q_{PS}\)). In fact, our image analysis system can only be performed in a small processing parameter range because one encounters two restrictions for higher flow rate ratios. First, due to large aspect ratio the wave is not homogeneous in the spanwise direction and a superposition of waves is recorded through the glass. Second, the nonlinear regime is reached rather rapidly and the linear region is too small to compute accurately the spatial growth rate.

In the following, we observe the behaviour of a defect generated by controlled perturbations at selected frequencies \(N\) defined in Table 1. The defect is in this case two-dimensional and it is possible to analyze precisely the spatial growth of the amplitude and the development of the wave in the channel. Let us illustrate this at frequency \(N = 0.49\) Hz:

<table>
<thead>
<tr>
<th>External forcing (N(\text{Hz}))</th>
<th>0.26</th>
<th>0.49</th>
<th>0.64</th>
<th>0.85</th>
<th>1.26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsation (\omega_r) (rad/s)</td>
<td>1.63</td>
<td>3.08</td>
<td>4.02</td>
<td>5.34</td>
<td>7.92</td>
</tr>
<tr>
<td>Time periodicity (T(s))</td>
<td>3.92</td>
<td>2.06</td>
<td>1.56</td>
<td>1.17</td>
<td>0.80</td>
</tr>
<tr>
<td>Velocity (V_d) (mm/s)</td>
<td>5.68</td>
<td>6.22</td>
<td>5.40</td>
<td>5.08</td>
<td>4.97</td>
</tr>
<tr>
<td>Wavenumber (k_r) (rad/mm)</td>
<td>0.28</td>
<td>0.50</td>
<td>0.74</td>
<td>1.05</td>
<td>1.59</td>
</tr>
<tr>
<td>Spatial periodicity (\lambda) (mm)</td>
<td>22.27</td>
<td>12.69</td>
<td>8.44</td>
<td>5.98</td>
<td>3.95</td>
</tr>
</tbody>
</table>

Table 1. Summary of defect features as a function of forcing frequency
Fig. 14. Sequence of photographs observed in x–y plane near the die exit (30 mm ≤ x ≤ 35 mm) of a perturbed flow at frequency 0.49 Hz; time interval between each shot is 0.08 s. Die edges are drawn on each shot.

Fig. 15. h(t) diagrams obtained from the sequence shown on Fig. 14 (forcing frequency 0.49 Hz) at successive positions between x = 31 mm and x = 35 mm.

Fig. 16. h(t) diagram obtained at a forcing frequency 0.64 Hz near the die exit (position x = 37 mm), observation of a nonlinear regime.
Fig. 13 shows a two dimensional wavy aspect. The distortions on edges are due to sticking of polymers on the lateral windows.

- Perturbations generated remain of small amplitude and difficult to observe for $0 \leq x \leq 30$. Fig. 14 shows a photograph sequence of interface through transparent windows in the range $30 \text{ mm} \leq x \leq 35 \text{ mm}$ at time interval of 0.08 s. One observes that the defect generated by controlled perturbation is advected and spatially amplified downstream.

- Fig. 15 shows diagrams $h(t)$ in the range $0 \leq t \leq 10 \text{ s}$ obtained by image analysis at positions $x = 31 \text{ mm}$, $32 \text{ mm}$, $33 \text{ mm}$, $34 \text{ mm}$ and $35 \text{ mm}$. It is first observed that the diagram $h(t)$ presents only one period and that amplitudes of oscillations are increasing with $x$. It is also observed that the interface profile is different from the imposed sinus perturbation which points out that higher order harmonics are activated or that the regime is nonlinear. This phenomenon appears clearly in Fig. 16 showing diagrams $h(t)$ at position $x = 37 \text{ mm}$ for a forcing frequency $N = 0.64 \text{ Hz}$. This phenomenon can also be detected on the extrudate in which two periods are observed (see Fig. 17).

4.4 Interface Defect Analysis in the Linear Regime

The signal $h(t, x)$ can be precisely studied when remaining in the linear regime. The wavy behaviour of the interface deviation is classically analyzed as a spatially dependent travelling wave in the form $h(t, x) = \exp(i(o_t t - k_x x))$ with $k = k_r + i k_i$, where $\omega_r$, $k_r$ and $k_i$ denote respectively the time pulsation, the wavenumber and the spatial amplification factor. Parameters $\omega_r$ and $k_r$ are related to the forcing frequency $N$, the spatial wavelength $\lambda$, and the phase velocity $V$ by the following relationships:

$$\omega_r = 2\pi N, \quad \lambda = 2\pi / k_r, \quad V = \omega_r / k_r$$

They are determined as follows:

- The time pulsation $\omega_r$ is first checked to be independent of the observation position $x$. It is observed on Figs. 15 that about 5 oscillations are found in a time interval of 10 s resulting in $\omega_r = 3.08$ ($N = 0.49$).

- The phase velocity $V$ is the velocity of the zero value of the interface deviation (see Fig. 18). It is estimated by determin-

Fig. 17. Photograph of extrudate obtained at $180^\circ \text{C}$, for $Q_{\text{PE}} = 87.4 \text{ g/min}$ and $Q_{\text{PS}} = 7.4 \text{ g/min}$. Die gap is 2 mm, forcing frequency is 0.64 Hz. Focus on the two main frequencies of interfacial wave

mining positions $x$ and $x + \Delta x$ at time $t$ and $t + \Delta t$ of the same zero value occurrence of the interface deviation. The phase velocity of the defect is then given by $V = \Delta x / \Delta t$. This value is checked to be independent of $x$ and the zero value selected (for example value A or B in Fig. 18). The wave number $k_r$ is then computed by $k_r = V \omega_r$. Results summarized in table 1 show that wavenumber is strongly dependent on the forcing frequency.

- The spatial amplification factor $k_i$ is determined by the slope of the graph of $\ln(h(t, x))$ as a linear regression of $x$. This analysis is in accordance with the hypothesis of an exponential growth of the defect in the linear regime. This is clearly identified on Fig. 19 at a forcing frequency $N = 0.49 \text{ Hz}$. One observes on Fig. 20 that the growth factor $k_i$ is strongly dependent on the wavenumber. Amplification is small at low wavenumbers, reaches a maximum at moderate wavenumbers $k_r \approx 1 \text{ rad/mm}$ and decreases for large wavenumbers. The amplitude of the defect remains small at frequencies $N = 0.26$ and $N = 1.26$ leading consequently to relatively large error bars on the growth factor $k_i$. However these results point out, in agreement with Wilson and Khomami’s observations [10], the selection of a dominant wavenumber for the defect.

Fig. 18. Detection of the zero value occurrences of the interface deviation

Fig. 19. Spatial growth rate of the perturbation for forcing frequency 0.49 Hz; the linear regression on a $(x, \ln(h(x)))$ diagram (logarithm of interface deviation as function of position) gives a slope of 0.1544/mm
4.5 Preliminary Conclusion

Experimental results obtained with device 2 point clearly out once again the convective nature of interfacial instability. It was first observed that intrinsic perturbations of the system give rise, in unstable processing conditions, to defects of increasing amplitude as travelling downstream. For spontaneously unstable flow the interface defect, generated by a random initial perturbation, leads to defects having a complex shape (Figs. 10 to 12) and their spatial periodicities are difficult to estimate. By using a periodic forcing device, in slightly unstable processing conditions corresponding to an apparently stable extrudate, it is possible to observe the spatial development of a two dimensional defect. Moreover, the spatial amplification rate depends on perturbation wavenumber.

5 Conclusion

These experiments show unambiguously the convective character of interface instability in coextrusion process and the link between the defects obtained on final extrudate and the wave observed within the die. The leading parameters for the onset of interface instability are flow rate ratio, q, and, at a minor extend, the total flow rate (which is similar to the mean shear rate).

In spontaneous unstable conditions, one observes in both devices a specific flow length for the onset of instability. The wave invades rather quickly the volume of the final part of the die and it is very difficult to determine accurately its amplification growth rate. In particular, the characteristics of final extrudates can depend on canal length. Note also that the width aspect ratio is an important parameter: for small values (1:4 in device 1 and 1:10 in Khomami’s apparatus) an uniform wave flows downstream, whereas for larger values (1:100 or 1:50 in device 2) the wave is not uniform in the spanwise direction.

In forced unstable conditions (coming from a controlled perturbation in a slightly unstable flow), it is possible to observe precisely the exponential development of interface wave. Measurements of linear spatial growth rate are made. It is found that growth rates are bigger than those found in Khomami’s experiments [10]. That probably comes from high elasticity of the polystyrene and the polyethylene used in our experiments. Moreover, the growth rate depends on the frequency of controlled perturbation and a dominant bandwidth frequency is selected by the PE/PS system. This explains the relatively regular wavy pattern observed within the die and on the final extrudate.

It is interesting to collect all experiments performed on the PE/PS coextrusion system at T = 180 °C described in the present paper and in a previous one (with coat hanger industrial die geometry, [15]). In fact, these experimental data cover a large range of operating conditions and different geometries. The extrudate aspects are reported in figure 21 in which they are expressed in the flow rate ratio (q = QPE/QPS) and average shear rate (γ) plane. The average shear rate γ can be defined as in [15] by γ = (QPE + QPS)/(Wd²) where W and d are respectively the die width and the die gap. Experimental results are compared to longwave stability analysis performed with viscoelastic White-Metzner constitutive equation [15].

As the agreement is fair, this shows clearly that despite the various features of extrudates and extrusion conditions, all these defects have a common hydrodynamic origin related to the interfacial wave between the two layers. However it was also found in [15] that, at higher temperatures, there are discrepancies between experiments and long wave stability analysis.

The experiments described in this paper as well as these discrepancies observed at higher temperature justify the use of convective stability analysis in order to predict in a better way the quality of multilayer polymer films produced with coextrusion process.
References


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