Formation of structures with dual phase continuity during flow of a PS/PMMA blend

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FORMATION OF STRUCTURES WITH DUAL PHASE CONTINUITY DURING FLOW OF A PS/PMMA BLEND.

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1 INTRODUCTION

A great amount of research has been performed in the field of multiphase systems. This has, among others, resulted in models that describe the break-up and coalescence of single droplets [1,2,3]. During the processing of immiscible polymer blends, where a large number of droplets exist, these phenomena also play a role. Lyngå Jørgensen and Valenza have used this as a base for their model for structure development [4]. The model predicts, at least quantitatively, the influence of volume-fraction and shear stress on domain-form and -stability of the dispersed phase in a simple shear flow.

The mechanical behaviour of polymer blends depends mainly on the mechanical properties of components and interface, and on the morphology. The model of Lyngå Jørgensen and Valenza is therefore valuable, since it gives indications for the processing conditions to obtain certain morphologies, as in situ fiberlike droplets and cocontinuous interpenetrating systems. The application is as yet restricted, due to the unstable behaviour of the structures during cooling and the non-steady state conditions in processing equipment.

The purpose of this project is to compare experimentally observed threshold values for the formation of cocontinuous interpenetrating structures with theoretical values, based on the percolation theory and the model for structure development. Furthermore, an experimental study of structure orientation, formation, break up and rate of change in the dual phase continuity area is performed and compared with the rheological properties of the selected blend, which consists of PMMA with eight weight-percent PS.
2 THEORY

2.1 Structure development

The model for structure development is based on the assumption that the dispersed phase of a blend (fraction $\phi$) in shear flow can be divided into small spherical and longer fiberlike droplets (fraction $\phi_s$ respectively $\phi_l$). The average length of the fiberlike droplets is defined as $a_l$, the ratio length/width as $P(=a_l/a_{11})$.

The aim of the model is to describe the system geometry ($a_l$, $\phi_s$ and $P$) in a steady state shear flow. The assumptions that have been used to solve the problem are [1,3]:

* The number-rate of small particles that are destroyed by coalescence is equal to the number-rate of small particles formed by breakup of the long droplets.

* The average domain size of the long particles is constant.

* The rate of domain deformation is depending on matrix viscosity and the first normal stress difference in the matrix and in the domains.

The equations that result from these assumptions can be simplified to give the following functions [4]:

\[ P = \frac{4\phi_w}{\pi k_i k_r (\alpha - 1)} \frac{q}{2} \quad (1) \]
\[ a_{11} = \frac{\pi \sigma P^2}{8 k r \bar{W}_t \varphi} \quad (2) \]
\[ \phi_l = \frac{\pi K^2 \sigma}{8 k r^4 a_{11}^4 \bar{W}_s} \quad (3) \]

where:

$\bar{W}_t$ = probability of coalescence at collision

$k_i$, $\alpha$ and $q$ = constants

$\tau$ = shearrate

$K = \bar{\gamma} \dot{\gamma}$ = shearrate

$\sigma$ = interfacial tension (See appendix 1)
2.2 Percolation threshold

The percolation threshold for the formation of a cocontinuous structure is the point where both phases each form an infinite structure. At this point the average product of the volume fraction ($\phi$) times the number of contacts between particles of the minority phase ($z$) equals one [5].

In appendix 2 the value for a highly simplified system containing both spherical and fiberlike droplets is derived, to give:

\[
\varphi_{cr}^{-1} = \frac{\varphi_s^2}{\varphi^2} + (4 + \frac{2}{P}) \frac{\varphi_s \varphi_l}{\varphi^2} + (4P+2) \frac{\varphi_s \varphi_l}{\varphi^2} + (8 - \frac{2}{P}) \frac{\varphi_l^2}{\varphi^2}
\]

(4)

For a blend that contains fiberlike droplets ($\varphi_l > 0$ and $P > 1$) this formula predicts a threshold at lower fractions than a blend that contains only spherical droplets ($\varphi_l = 0$).
3 EXPERIMENTAL SET UPS

In order to test the applicability of the theory, the morphology of the blend must be known at different shear rates. Therefore a simple shear flow is generated in a mechanical rheometer (Rheometrics RMS), in which the blend is placed between a rotating cone and a plate. The morphology that develops is evaluated using two different methods. They will be discussed in the following.

3.1 Electron microscopy and image processing

In a transmission electron microscope an image is created by the amount of electron radiation, that shines through a sample [6]. This sample is a thin slice of the blend, cut by a so-called microtome. The blend has been quenched (shock-cooled) immediately after shearing in the rheometer, in order to prevent break up of the long droplets. At each point in the material two samples are made, in and perpendicular to the flowdirection. Special attention has to be paid to the cutting direction, since a slight deflection will lead to a change in the measured sizes, especially of the long droplets.

The electron microscope pictures are evaluated using a computer with image processing software in combination with a CCD-camera. To make a distinction between the droplets an arbitrary 'cut off' length has to be chosen. The particles below this value are thought to be spherical, the rest long fiberlike. First the average $a_{||}$-axis is determined from the picture perpendicular to the flow-direction (fig.1). This value is then used as the cut off length when examining the picture in the flow-direction, so that the average $a_{\perp}$ value of the long particles can be measured (fig.2).
3.2 Laser light scattering

For characterisation of polymer structures numerous methods are used, based on the diffraction of radiation. Laser light diffraction is one of these methods, that can be used to analyze morphologies of polymer blends at processing temperatures [7,8]. In this case the basic principle is the difference in the local radii of an elongated droplet, which causes a difference in the scatter angles.

In order to measure the scattering signals, the rheometer is equipped with a glass cone-plate configuration (fig. 3). A

![Schematized operation of light-scattering](image)
laserbeam is directed at the blend and the scattered signals, in and perpendicular to the flow-direction, are recorded at certain discrete angles by means of a lightsensor. The averaged absolute ratio of the droplets can be derived from these signals using a calibration curve between the light scattering and the microscopy data (fig. 4).

This calibration curve is needed, because the light scatter ratio is a rather arbitrary value. It is dependent on the chosen scatter angle. Moreover, the intensity is mainly a measure for the volume-fraction and size of the spherical droplets, the longer droplets cause less scattering. The ratio of intensities found by light scattering is therefore a measure for the difference in the number of small radii in both directions.

The main advantage of the laser light scattering equipment is its ability to monitor time effects, for instance the rate of change of the morphology. A drawback is that different morphologies may give identical scatter patterns. This means that laser scattering should always be used in combination with another technique.
4 RESULTS

The experimental set ups, described in the previous chapter, can in principle be used to test the theory. Therefore the fractions \( \phi_i \) and the ratio \( P \) at a certain shearrate should be calculated with the model for structure development and be inserted in the model for the percolation threshold, that predicts the existence of a cocontinuous structure. This prediction will not be very accurate as a result of the propagation of errors, made in the characterisation of materials. There is also an addition of model-errors in successively the models for coalescence, break up, structure development and percolation threshold. The influence of each of the formulas on the final deviation can be analyzed by comparing the predicted and measured values for \( P \), \( a_i \), \( \phi_i \), and \( \phi_{cr} \). In case of a difference, the measured value should be inserted and a new calculation made.

4.1 Characterisation of the materials

The components used in the blend are poly-methylmethacrylate and poly-styrene. Their properties are listed in table 1.

<table>
<thead>
<tr>
<th>component</th>
<th>supplier</th>
<th>( \eta_0,180^\circ C )</th>
<th>( M_w )</th>
<th>( M_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS</td>
<td>Shell N 3000</td>
<td>3.2 ( 10^4 )</td>
<td>3.1 ( 10^5 )</td>
<td>4.5 ( 10^6 )</td>
</tr>
<tr>
<td>PMMA</td>
<td>Polysar 210</td>
<td>2.2 ( 10^5 )</td>
<td>9.1 ( 10^4 )</td>
<td>3.7 ( 10^4 )</td>
</tr>
</tbody>
</table>

In an open cone plate configuration the normal stress cannot be measured at shearrates in excess of 1 [1/s]. At higher rates the material flows out of its holders, probably due to a minor misalignment (See appendix 3). However, the approximate behaviour at higher rates is known from literature (fig. 5).

The blend consists of 92 volume per cent of PMMA and 8 per cent of PS. It is premixed in a Brabender Plasticorder (Mixing head Walzenkneter 30, 10 minutes at 180°C , 20 rpm). A press
5. Normal stress behaviour of dispersed phase

is used to obtain the desired sheet-thickness (2 min. preheating at 210°C, 3 min. pressurized at 5 bar).

4.2 Laser light scattering

To prevent the flow out of material at higher shear rates, a closed geometry is created by placing a ring around the glass cone and plate. This causes a slightly imperfect flowfield in the surrounding and an extra torque (friction) during shearing.

Four different measurements have been performed. In each measurement the shear rate is adjusted to a desired initial value. When the light scatter ratio reaches a steady state value, the rate is changed until the selected range has been covered. During each test recordings are made of the torque, light scattering, transmission (angle = 0), shear rate and time. These signals have to be corrected for the extra torque caused by the ring and for the actual shear rate (Appendix 4). The resulting steady state light scatter ratios are plotted in figure 6 as a function of shear stress.
The main observations that can be made from figure 6 are:

* A maximum exists near the point where the normalstress coefficient $\alpha$ alters, as predicted by formula 1 and figure 5.

* No elongated droplets appear to be formed, when a big step in shearstress is made (numbers 2 and 3). The same phenomenon has been observed by Hinch and Acrivos [1]. However the electron microscopy does not confirm this observation.

A very remarkable behaviour is observed in measurement 2, where the recording continues during the cooling process. It shows an increasing aspect ratio, even under the glass-transition temperature (appendix 4). This change, partly caused by the thermal expansion of the sensor, was confirmed after realignment at room-temperature.
4.3 Electron microscopy and image processing

In appendix 5 the microscopy pictures and their flow-history are listed. Since the institute's electron microscope was out of order during the project, these pictures were taken later. As a result of this no matching calibration curve could be made.

In order to proceed with the project another set of pictures has been evaluated. These were made of a blend that contains a home-made polystyrene with a narrow weight-distribution. The results of this evaluation are shown in figure 7. It illustrates the cut off lengths influence. Curve 1 is the most realistic, where the length is the mean plus standard deviation of the particles in the picture perpendicular to the flow direction. The ratio at \( \dot{\gamma} = 0.078 \) is very low, probably due to an incorrect cutting direction. A possible curve-fit will be very sensitive to the values of the three remaining points.
5 DISCUSSION

Since the explicit calibration-curve and course of the normal stress are unknown, the experimental values cannot be compared with the theory. Nevertheless the light scatter data seems to be in qualitative accordance with the model for structure development. The elevation of the theoretical maximum is highly dependant on the transition of the normal stress-coefficient \( \alpha \) and its corresponding shear stress value.

Extra attention has to be paid to the changes in the morphology during cooling. These changes may partly be caused by a difference in thermal expansion of the components. A result of this change might be that a correction is needed in the TEM-calibration.

If all quantities in the model are assumed to be measured accurately and the shear rate of the theoretical maximum to correspond to the light scatter-maximum, then it is found that \( P_{\text{max}} = 16 \) and \( \varphi_s/\varphi = 0.01 \) [4]. The calculated percolation threshold fraction is equal to 0.119. Since this value is larger than the actual fraction, no cocontinuous structure is predicted. This conclusion is confirmed by the microscopy pictures of the blend.

In a former experiment the following values were found: \( P = 20 \) and \( \varphi_s/\varphi = 0.07 \). These give a theoretical threshold value of 0.08. The observed value was 0.113. Since the threshold values range from 0 to 0.156, this is a large deviation.

The current prediction of the threshold fraction using the percolation theory on a highly simplified system is not very accurate. Since the mechanical behaviour of cocontinuous structures can be described successfully in terms of the threshold fraction, more effort should be put into increasing the precision of this estimate.
REFERENCES


APPENDIX 1: Measurement of interfacial tension

The interfacial tension ($\sigma$) between two molten polymers is of major importance on the development of blend morphology and therefore included in the model for structure development. One way in which this tension can be determined is the so-called breaking thread method [Elemans, Janssen and Meyer. J. Rheol 34(8), November 1990].

In this method a thread of one polymer is placed between two films of the second. This system is placed in an oven (Mettler FP2 hot stage). At certain time intervals pictures are made of the resulting breakup process. The surface tension can be calculated from the grow rate of distortions on the thread ($q$):

$$\sigma = q\eta_c D_0 / \Omega_n$$

were:

$\eta_c$ = viscosity of matrix phase

$D_0$ = original thread diameter

$\Omega_n$ = a tabulated function of the viscosity ratio

$\alpha$ = amplitude of distortions = $a_0e^{qt}$

Since the breakup times are highly dependant on the viscosity of the components, the experiments are carried out at 220°C in order to achieve an acceptable duration. The influence of temperature on the surface tension can be found in Wu [Polymer interface and adhesion]. The viscosity of the components at this temperature is measured on a RDS-II rheometer:

$\eta_{ps} = 3.2 \times 10^3$ and $\eta_{pena} = 7.3 \times 10^3$ Pa.s., which finds $\Omega_n = 0.11$.

In this project three clear series of pictures have been made. Only one however displays a successful effort, were the dominant wave number $\chi_n(=2\pi R_0/\lambda_n)$ is close to the theoretical one. Table A1.1 contains the data, that has been obtained from these pictures (fig. A1). The relative grow rate $q$ is found
from a linear regression of the data sets \((\ln(2c/D_0), \text{ time})\) :
\[q=0.0020 \text{ [l/s]}. \text{ (correlation coefficient= 0.994)}\]

<table>
<thead>
<tr>
<th>number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>time</td>
<td>0 s.</td>
<td>360</td>
<td>780</td>
<td>1170</td>
<td>1380</td>
</tr>
<tr>
<td>(2\alpha/D_0)</td>
<td>0.044</td>
<td>0.105</td>
<td>0.289</td>
<td>0.526</td>
<td>0.719</td>
</tr>
</tbody>
</table>

The surface tension can now be calculated with the above formula \((D_0= 0.071 \times 10^{-3} \text{m.})\) :

\[\sigma= 9.6 \times 10^{-3} \text{ N/m}.\]

Usually this tension is calculated as the averaged value of several measurements.

fig. A1
APPENDIX 2: Calculation of percolation threshold value

At the percolation threshold the average product of volume fraction ($\varphi$) times the number of contacts ($z$) is equal to one. The value of $z$ depends on the geometry of the system. Since the real geometry is complex, two simplifications are made:

* The distribution of the dispersed phase consists only of small spherical and longer fiberlike droplets.
* One long droplet is a cluster of $P$ spherical droplets in a row.

An approximation for the number of contacts can now be found by placing the orientated droplets in a cubic lattice. The contacts of a droplet of length $t$ to a droplet of length $r$, which is placed on an arbitrary location, can be split into:

Contact to a side.

probability (location is occupied by $r$) := $\varphi_r/\varphi$
number of ways to contact side (fig A2) := $t + r - 1$.
probability (one way to make contact) := $1/t * \varphi_r/\varphi$
number of sides in cubic lattice := $4$ x

Contact to an end.

probability (location is occupied by $r$) := $\varphi_r/\varphi$
probability (one way to make contact) := $1/t * \varphi_r/\varphi$
number of ends (fig A2) := $2$ x

A2. contact to a side contact to end

16
Total.

- small contacts small droplet \( t := 1 \quad r := 1 \)
- long contacts small droplet \( t := P \quad r := 1 \)
- small contacts long droplet \( t := 1 \quad r := P \)
- long contacts long droplet \( t := P \quad r := P \)

\[
z := 6 \frac{\phi_s^2}{\varphi^2} + (4 + \frac{2}{P}) \frac{\varphi_l \varphi_s}{\varphi^2} + (4P+2) \frac{\varphi_l \varphi_l}{\varphi^2} + (8 - \frac{2}{P}) \frac{\varphi_l^2}{\varphi^2}
\]

This estimate of \( z \) is a maximum value, since multiple contacts to one site are not excluded. For a system containing only spherical droplets \( (\varphi_l = 0) \) the theoretical threshold value is found to be \( \varphi_{cr} = 0.156 \) [5]. The above formula gives \( \varphi_{cr} = 0.167 \). A deviation of 6.8 %.

This deviation may be decreased by increasing the models accuracy, for instance by

- using the particle size distribution in stead of the averaged ratio \( P \). Long droplets contribute more to the decrease in fraction.

- analysis of the dependency of the probability of coalescence at collision \( W \) on the way of contact.
APPENDIX 3: Characterisation of components
APPENDIX 4: Light scatter measurements

In this appendix the results of the light scatter measurements are plotted. The plots show the ratio of the intensities measured at 7.5° as a function of time. The two top frames of each plot contain the intensity as a function of the scatter-angle and a reconstruction of the droplet-shape at a certain time. In table A4-1 a survey of the steady state ratios is given.

To prevent the flow-out of material the measurements are performed in a closed cone-plate configuration. As a result of this the shear stress cannot be measured accurately simultaneous to the light scatter measurements. The shear stress is therefore reconstructed using a plot of the viscosity as a function of shear rate, measured in an Instron capillary viscosimeter. This may introduce an error since a different flow-field is generated. The variation is analyzed by comparing the measured and reconstructed values (page 23). The actual rotation speed of the rheometer can be found from the calibrations in table A4-2.

![Intensity vs. Angle and Viscosity vs. Shear Rate graphs]

Date: 02/15/91  File: PMMA/PSB.001
Sample: PMMA/PS-8/92  Temp.(°C): 180
Step rate sweep
Time from start in [min]: 35
Date: 02/15/91 File: PNNAPS8.01A
Sample: PMMA/PS-8/92 Temp.[C]: 180
Single step rate
Time from start in [min]: 25

Date: 02/15/91 File: PNNAPS8.01A
Sample: PMMA/PS-8/92 Temp.[C]: 180
Single step rate
Time from start in [min]: 15
Date: 02/15/91 File: PMMAPS8.002
Sample: PMMA/PS-8/92 Temp.[°C]: 180
Single step rate
Time from start in [min]: 7

Date: 02/15/91 File: PMMAPS8.003
Sample: PMMA/PS-8/92 Temp.[°C]: 180
Single step rate
Time from start in [min]: 16
### Table A4-1, steady state ratio's.

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<tr>
<td>$\omega_{\text{nom}}$ [rad/s]</td>
<td>$\tau_{\text{instr}}$ [Pa]</td>
<td>ratio P</td>
<td>time at rate</td>
<td></td>
</tr>
<tr>
<td>0.0004</td>
<td>7.48e3</td>
<td>3.02</td>
<td>8.0 min</td>
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<tr>
<td>0.001</td>
<td>1.87e4</td>
<td>2.94</td>
<td>4.6</td>
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<td>3.54</td>
<td>5.7</td>
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<tr>
<td>0.0025</td>
<td>3.4 e4</td>
<td>3.74</td>
<td>5.9</td>
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<td>0.004</td>
<td>4.17e4</td>
<td>3.83</td>
<td>7.9</td>
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<td>0.01</td>
<td>6.3 e4</td>
<td>1.75</td>
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<td>0.025</td>
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<td>0.063</td>
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<td>1.06</td>
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<td>0.25</td>
<td>1.45e5</td>
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<td>0.0001</td>
<td>1.8 e3</td>
<td>1.30</td>
<td>61**</td>
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<td>0.0025</td>
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<td>1.43</td>
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<td>0.0063</td>
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<td>1.55</td>
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<table>
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<td>0.0025</td>
<td>3.4 e4</td>
<td>1.34</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

**note:**

* Measurement PMMAPS8.01A should be regarded with care, since the connection of the glass-cone and its holder was partly loose.

** If a steady state situation is assumed to be reached after the same shear $\gamma$ in each measurement, then this measurement shows that the ratio found in measurement PMMAPS8.001 at $\omega=0.0004$ is probably not a steady state value, since the total shear $\gamma = \dot{\gamma} \cdot t = k \omega t$ is smaller. The times at higher rates are rather short, but here only relatively small changes in morphology occur as a result of a limited increase in shear rate. This is in contrast with the first rate where there the morphology results from a change from mixing and pressing to shearing.
<table>
<thead>
<tr>
<th>nominal speed</th>
<th>actual speed</th>
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<tbody>
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<tr>
<td>0.10 * 0.001</td>
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<tr>
<td>10 * 0.001</td>
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<tr>
<td>1.00 * 0.001</td>
<td>0.0015</td>
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<tr>
<td><strong>discrete setting</strong></td>
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<td>0.0014</td>
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<td>0.0016</td>
<td>0.0020</td>
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<td>0.0025</td>
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<td>0.0042</td>
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<tr>
<td>0.0063</td>
<td>0.0066</td>
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</tr>
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<td>0.040</td>
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<tr>
<td>0.063</td>
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</tbody>
</table>
APPENDIX 5: Survey of microscopy pictures

In this survey the pictures made in the flow direction are presented on the left side of the page. The pictures perpendicular to the flow direction on the right. All pictures show the blend at a scale 13333:1.

During the project pictures have been made of samples from seven measurements, that can be divided into three groups:

A5.1 Pictures from the RDS-II rheometer

<table>
<thead>
<tr>
<th>sample 1</th>
<th>configuration</th>
<th>conditions</th>
<th>duration</th>
<th>comment</th>
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</thead>
</table>
|          | plate-plate, radius= 12.5 mm., gap= 1.5 mm. | \(\dot{\omega} = 0.1\) rad./s., quenched | \(\text{total} = 4\) min. | These pictures are made of a blend that has been deformed rather short. It was falsely assumed that the time to equilibrium of viscosity and morphology are identical. The first light scatter data contradicted this assumption. Although not in steady state, the pictures show the tendency of the long semiaxis \(a_{II}\) to increase at these shear rates, as predicted.

shearrate \(\dot{\gamma} = 1.3\) e-1
A5.2 Pictures from the light scatter samples (RMS)

sample 2
configuration: cone-plate, radius = 14 mm., $\beta = 0.7$, closed geometry
conditions: $\omega$ (end) = 0.25 rad./s., slow cooling.
duration: time at last rate = 3.5 min, total = 80 min.
remarks: used for scattering (pmmaps8.001)
comment: Although the long droplets have changed during the cooling by breakup, relaxation and/or coalescence, it can be deduced that the average radius of the unchanged small droplets is smaller than in the previous pictures, as predicted by the theory.
shearrate $\dot{\gamma} = 2.05 \text{ e1}$

sample 3
configuration: cone-plate, radius = 14 mm., $\beta = 0.7$, closed geometry
conditions: $\dot{\gamma} = 0.004 \text{ rad./s.}$, slow cooling
duration: total = 19 min
remarks: used for scattering (pmmaps8.002)
comment: This picture is a clear illustration of the break up process caused by the so-called Rayleigh distortions above the glass transition temperature. This breakup causes a decrease in ratio and contrasts therefore with the increase observed with the light scatter equipment.

shearrate $\dot{\gamma} = 3.3 \text{ e-1}$
sample 4
configuration : cone-plate, radius= 14 mm., $\beta$= 0.7, closed
geometry
conditions : $\dot{\gamma}$= 0.025 rad./s., quenched
duration : total= 14 min
remarks : used for scattering (pmmaps8.003)

shearrate $\dot{\gamma}$= 2.05 el

A5.3 Pictures to be used for calibration (RMS)
(samples reproduced in increasing shearrates)

sample 6
configuration : plate-plate, radius= 25 mm., gap= 0.80 mm.,
closed geometry
conditions : $\dot{\gamma}$= 0.016 rad./s., quenched
duration : time at last rate= 4.6 min, total= 10.2 min.
shearrate $\dot{\gamma} = 1.0 \ e^{-1}$

shearrate $\dot{\gamma} = 1.7 \ e^{-1}$

shearrate $\dot{\gamma} = 3.0 \ e^{-1}$
Sample 7

Configuration: Plate-plate, radius = 25 mm., gap = 0.95 mm.
Conditions: \( \dot{\theta} = 0.063 \text{ rad./s.}, \) quenched.
Duration: Time at last rate = 4.8 min, total = 9.8 min.

Shear rate \( \dot{\gamma} = 3.9 \times 10^{-1} \)

Shear rate \( \dot{\gamma} = 6.7 \times 10^{-1} \)

Shear rate \( \dot{\gamma} = 1.2 \times 10^{0} \) (slight deviation from flow-direction)
sample 5
configuration : plate-plate, radius= 18 mm., gap= 0.19 mm.
conditions : \( \omega = 0.063 \) rad./s., quenched
duration : time at last rate= 7.6 min, total= 21.6 min.
comment : These pictures show the blend at shear rates near the observed maximum of the ratio \( P \). The picture in flow direction is probably made of a non flat specimen. The picture perpendicular to it is very different from the others and might illustrate a local cocontinuous structure (\(?\)).

shear rate \( \dot{\gamma} = 2.5 \times 10^0 \)

shear rate \( \dot{\gamma} = 5.3 \times 10^0 \)