Kickdown meeting
‘Advanced Rheology’
2 March 2017

The development and validation of an extrusion modelling procedure to simulate extrudate swell.
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Project Plan

1. Literature Research
2. Rheological measurements
3. Viscoelastic models
4. Extrudate Swell Simulations
5. Simulations <-> Experiments
6. Validation of the procedure
7. Extrudate Swell Experiments
Conclusion literature report:

‘The studies do not give a clear example how to determine the best viscoelastic model for a specific fluid and/or what an appropriate procedure is to model extrudate swell’.

Additional insights from literature:

- PTT (Phan-Thien Tanner) model is widely applicable
- Wall slip is an important factor even at low shear rates
- Extrapolation of apparent shear viscosity

For example:

Chuan Yang and Ziran Li (2016), *Effects of wall slip on the rheological measurement and extrusion die design of a filled rubber compound, Plastics, Rubber and Composites* 45:7, 326-331
3 tire rubber compound

- Side wall compound
- Tread compound for a winter tire
- Tread compound for a summer tire

- The rubber compounds are used for extrudate swell experiments
- Rheological measurements of $G'$, $G''$ and $\eta$ are needed for fitting a viscoelastic model
- RPA2000 – oscillatory cone-cone rheometer
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Rheological measurements

Storage \( G' \), Loss \( G'' \) and viscosity \( \eta \) at 90°C

Compound 701 at 90°C

Compound 719 at 90°C

Compound 720 at 90°C
Rheological measurements

Viscosity of the different compounds at 90°C

<table>
<thead>
<tr>
<th>Rubber</th>
<th>η [Pa s] at 1,5 s⁻¹</th>
<th>η [Pa s] at 209 s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>701</td>
<td>68164</td>
<td>1417</td>
</tr>
<tr>
<td>719</td>
<td>86112</td>
<td>1774</td>
</tr>
<tr>
<td>720</td>
<td>86047</td>
<td>2431</td>
</tr>
</tbody>
</table>
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Rheological measurements

Viscosity at temperatures from 90°C up to 120°C

η compound 701

η compound 719

η compound 720
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Viscoelastic models

- The PTT viscoelastic model:

\[
\epsilon \left( \frac{\varepsilon \lambda}{\eta_1 \text{tr}(T_1)} \right) T_1 + \lambda \left( 1 - \frac{\xi}{2} \right) T_1 + \frac{\xi}{2} \Delta T_1 = 2\eta_1 D
\]

- Parameters which can be curve fitted: \(\varepsilon\), \(\xi\), \(\eta_1\), \(\lambda\)

- A multimode viscoelastic model is composed of the sum of individual viscoelastic components.

- Up to 10 modes may be used in Polyflow, due to computational costs the first curve fits are with a 3 mode PTT.
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Viscoelastic models

Curve fit of the 701 compound at 100°C

\[ \eta^* = 85422 \omega^{0.24-1} \]
\[ G' = 72078 \omega^{0.26} \]
\[ G'' = \sqrt{\omega^2 \eta^{*2} - G'^2} \]
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Extrudate Swell Experiments

The Shark 70

<table>
<thead>
<tr>
<th></th>
<th>D(mm)</th>
<th>L (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6s</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>6l</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>12s</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>12l</td>
<td>12</td>
<td>10</td>
</tr>
</tbody>
</table>
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Extrudate Swell Experiments

P1: 30 bar
TD: 100 C
RPM: 20
Vc: 33,85 m/min

P2: 94 bar
T1: 75,6 C
T2: 86,5 C
TO: 103 C
Q: 241,2 kg/hr
D: 101,7 %
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Extrudate Swell Experiments

Compound: 701

\[ P_1 = 30 \text{ bar}, \quad T_{\text{die}} = 100 \text{ C}, \quad \text{extrudate swell at 10 mm}. \]
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Validation (6l, 701, 30 bar and 100°C)

Pressure drop:
- PTT simulation
- Experiments

Extrudate swell:
- Experiments
- PTT simulation
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The first extrudate swell simulations

Die: 6mm diameter, 10 mm long, 10 mm extrudate

- A quarter of the die is simulated, symmetry axis are introduced
- High shear rates occur near the die exit (8000 1/s).
- No convergence of the simulation at higher flow rates

Convergence is achieved with wall-slippage

- Distortion of the extrudate swell
- Overprediction of the pressure drop inside the die (500 Bar)
- Overprediction of the extrudate swell

Several adaptation in order to simulate reasonable pressures and amounts of extrudate swell

- Mesh quality and refinement
- PTT curve fit with realistic shear rates
- Slip coefficient dependency on pressure and swell
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Mesh quality and refinement

an unstructured hexagonal mesh

a structured hexagonal mesh

a structured hexagonal mesh with refinement at wall

Hybride mesh with structured mesh in de die exit and unstructured mesh at the die inlet.
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Curve fitting with realistic shear rates

Complete die without extrudate and without wall-slip

Simulated shear rates mostly between 1.5 s⁻¹ and 900 s⁻¹

<table>
<thead>
<tr>
<th>Relaxation time</th>
<th>Shear rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00067 s</td>
<td>1500 s⁻¹</td>
</tr>
<tr>
<td>0.02 s</td>
<td>50 s⁻¹</td>
</tr>
<tr>
<td>0.6 s</td>
<td>1.67 s⁻¹</td>
</tr>
</tbody>
</table>

Curve fit on extrapolated data

G' and G'': Frequency [rad s⁻¹]
η: Shear rate [s⁻¹]
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Curve fitting with realistic shear rates

- **fitted relaxation times**
  - PTT1
  - PTT fit-$G'$
  - PTT fit-$G''$
  - PTT fit-$\eta^*$

- **chosen relaxation times**
  - PTT5

- **less $G''$**
  - PTT6

- **Pressure [Pa]**
  - $8 \times 10^6$
  - $9 \times 10^6$
  - $1 \times 10^7$
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Dependency on slip coefficient

![Graph showing dependency on slip coefficient](image)

- **Full slip**
- **No slip**

- **Pressure at die inlet [Pa]**
- **Slip coefficient used in the extrudate simulations**
- **Pressure as a function of wall-slip**
Pressure as function of gear pump speed for different slip factors and experimental values.
Swell profile as function of distance from the die exit for different slip factors and experimental values.

Extrudate swell simulation with a coarse mesh
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Validation (6l, 701, 30 bar and 100 C)

Swell at 10 mm from die exit for different flow rates
Conclusions

A procedure for extrudate swell simulation has been developed based on dynamic measurements of the rheological properties. Therefore:

- Accurate measurements of the rheological properties are needed in a shear rate range, which is actually occurring in your process.
- The process conditions, like pressure and extrudate swell, are highly dependent on grid quality and grid fineness.
- In order to obtain convergence a minimum amount of slip at the wall is needed.
- The simulated pressure drop is strongly dependent on wall slip and therefore to choose the right viscoelastic model this slip has to be excluded.

To validate this procedure extrusion experiments have been carried out for different process conditions, different die geometries and different rubber compounds.
The original GreenPAC ‘Advanced Rheology’ project finished in December 2016

To finalize the project:

• More validation of the simulation procedure has been carried out for:
  - more compounds
  - more die geometries (focus on the trapezium shaped die)

• The procedure has been extensively documented in an internal memo’s and in a scientific publication

Buist, J., Dijk, D.J. van and Mateboer, T.J. (2017) Tire rubber extrudate swell simulation and verification with experiments, Proceedings 2017 CFD conference in Trondheim
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Recommendations

The GreenPAC ‘Advanced Rheology’ project will be extended till December 2017 for a master thesis of Tijmen Mateboer

Subjects:

- Simulation with lower gear pump speeds and possibly compounds with varying carbon black concentration to exclude wall slip.
- Investigation of the influence of different viscoelastic models on extrudate swell