Autodesk Simulation Moldflow Analyses at the University of Bradford

Dr Fin Caton-Rose and Dr Ben Whiteside
The University of Bradford has been using Autodesk Simulation Moldflow software for many years to investigate key injection-molding effects such as fiber orientation, residual stresses, warpage, post-injection product performance, heat transfer, and feature replication. This class builds on our Autodesk University 2011 class and covers the experimental and computational analysis of short and long fiber reinforced components during injection molding, along with thermal investigations of the micromolding process.
At the end of this class, you will be able to:

- Select the most appropriate analysis route for product development
- Understand the validity of analysis results with a view to final product geometry and performance
- Explain the process being analysed for the injection moulding of polymer composites and micromouldings
- Apply best practices for in-house Autodesk Simulation Moldflow analyses, leading to finite element modelling
Short Glass Fibre Composites
Typical Fibre Orientation Sample
How to define fibre orientation distribution

a typical 2D image analysis section

the definition of the angles $\theta$ and $\phi$

$$\phi = 0$$

$$\phi = -90$$

$$\theta = \cos^{-1}\left(\frac{b}{a}\right)$$
Fibre Orientation Measurement System

- Sample Preparation
- Image Capture
- Threshold Image
- Large Area Reconstruction
- Ellipse Fitting

Elliptical parameters determined for each fitted ellipse (in red)

Multiple frames scanned in a raster fashion
fibres matched between frames
Samples Used for Fibre Orientation Calibration

Delphi

Bradford

Oak Ridge

BASF
Short Glass Fibre Composites

**End gated flat plates**
- 40 mm x 120 mm
  - 4 mm thick with a 1 mm gate
  - 2 mm thick with 0.5 mm gate
  - 2 sample locations

**Centre gated discs**
- 95 mm diameter
  - 1 and 2 mm thick centre plate
  - 3 sample locations

**Fatigue Sample**
- 45 mm x 150 mm
  - 3.5 mm thick
  - 2 injection points
  - 2 sample locations
# Moldflow Model
Midplane of 2 mm plate with 0.5 mm gate

2,000 elements
20 layers through the thickness
Lines of elements coincident with location of fibre orientation measurement

## Input Parameters for Folgar-Tucker and Modified Version of Folgar-Tucker

### Folgar-Tucker

<table>
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<tr>
<th>Model</th>
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### Modified Folgar-Tucker

<table>
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</table>
Folgar-Tucker

Location Through Thickness (mm)

Fibre Orientation

Experimental Data

Folgar-Tucker
Modified Folgar-Tucker ($D_z=0.8$)
Modified Folgar-Tucker ($D_z=0.6$)
Modified Folgar-Tucker ($D_z=0.4$)
Modified Folgar-Tucker ($D_z=0.2$)
Modified Folgar-Tucker Optimisation (Maximum)

![Graph showing Modified Folgar-Tucker Optimisation (Maximum)](image)

**Default**

\[ D_z = 0.3214 \]

\[ c_i = 0.0008 \]
Modified Folgar-Tucker Optimisation (Average)

Average Fibre Orientation vs. Fibre Interaction Coefficient

- Experimental Data

- Modified Folgar-Tucker Optimisation (Average)

Default
\( D_z = 0.3214 \)
\( c_i = 0.0008 \)
Modified Folgar-Tucker Optimisation (Minimum)

Fibre Interaction Coefficient vs Minimum Fibre Orientation

- Default: $D_z = 0.3214$, $c_i = 0.0008$
- Experimental Data

 sono Dz=1, Dz=0.8, Dz=0.6, Dz=0.4, Dz=0.2

\[ D_z \]
Optimum Modified Folgar-Tucker

<table>
<thead>
<tr>
<th>Optimum</th>
<th>Default</th>
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</thead>
<tbody>
<tr>
<td>(D_z = 0.15)</td>
<td>(D_z = 0.3214)</td>
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<tr>
<td>(c_i = 0.0057)</td>
<td>(c_i = 0.0008)</td>
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## Moldflow Model
Midplane of 2 mm plate with 0.5 mm gate

- 2,000 elements
- 20 layers through the thickness
- Lines of elements coincident with location of fibre orientation measurement

### Input Parameters for Reduced Strain Closure Model

<table>
<thead>
<tr>
<th>Model</th>
<th>k</th>
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</table>
Reduced Strain Closure ($k=0.8$)

Fibre Orientation

Location Through Thickness (mm)

- $c=0.1$
- $c=0.01$
- $c=0.001$
- $c=0.0001$
- $c=0.00001$

- Experimental Data
Reduced Strain Closure (k=0.6)
Reduced Strain Closure (k=0.4)
Reduced Strain Closure (k=0.2)
Reduced Strain Closure (k=0.01)
Reduced Strain Closure (k=0.001)
Reduced Strain Closure (k=0.0001)
Reduced Strain Closure (k=0.00001)
Reduced Strain Closure Optimisation (Maximum)
Reduced Strain Closure Optimisation (Average)
Reduced Strain Closure Optimisation (Minimum)
Optimum Reduced Strain Closure

**Optimum**

\[ k = 0.1 \]
\[ c_i = 0.0057 \]

- Experimental A
- Optimum A
- Experimental B
- Optimum B
Short Glass Fibre Composites

**End gated flat plates**
- 40 mm x 120 mm
- 4 mm thick with a 1 mm gate
- 2 mm thick with 0.5 mm gate
- 2 sample locations

**Centre gated discs**
- 95 mm diameter
- 1 and 2 mm thick centre plate
- 3 sample locations
Optimum Modified Folgar-Tucker (4 mm plate)

**Optimum**
- $D_z = 0.15$
- $c_i = 0.0057$

**Default**
- $D_z = 0.1579$
- $c_i = 0.001$

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**Diagram Details**

- **Experimental A**
- **Optimum A**
- **Default**

**Axes:**
- **Fibre Orientation**
- **Location Through Thickness (mm)**
Modified Folgar-Tucker Optimisation (Maximum)

- Default $D_z=0.1579$
- $c_i=0.001$
Modified Folgar-Tucker Optimisation (Average)

![Graph showing average fibre orientation against fibre interaction coefficient for different Dz values. The graph includes data points for Dz=0.1579 and ci=0.001.](image)

- **Default**
  - $D_z = 0.1579$
  - $c_i = 0.001$
Modified Folgar-Tucker Optimisation (Minimum)

- Fibre Interaction Coefficient
- Minimum Fibre Orientation

Experimental Data

Default
\[ D_z = 0.1579 \]
\[ c_i = 0.001 \]
Optimum Reduced Strain Closure (4 mm plate)

Optimum

\[ k = 0.1 \]
\[ c_l = 0.0057 \]
Reduced Strain Closure Optimisation (Maximum)

Maximum Fibre Orientation

Fibre Interaction Coefficient

- k=0.00001
- k=0.0001
- k=0.001
- k=0.01
- k=0.2
- k=0.4
- k=0.6
- k=0.8

Experimental Data
Reduced Strain Closure Optimisation (Average)
Reduced Strain Closure Optimisation (Minimum)

![Graph showing the relationship between Minimum Fibre Orientation and Fibre Interaction Coefficient.](image)

- **Minimum Fibre Orientation**
  - X-axis: Fibre Interaction Coefficient
  - Y-axis: Minimum Fibre Orientation

- **Key**:
  - k=0.00001
  - k=0.0001
  - k=0.001
  - k=0.01
  - k=0.2
  - k=0.4
  - k=0.6
  - k=0.8
  - Experimental Data

**Graph Details**
- The graph illustrates how the Minimum Fibre Orientation changes with varying Fibre Interaction Coefficients.
- Different colors and line styles are used to distinguish between various interaction coefficients.
- The Experimental Data is represented by a dashed line for comparison.
Optimum Modified Folgar-Tucker (1 mm disc)

Optimum

$D_z = 0.15$
$c_i = 0.0057$
Optimum Modified Folgar-Tucker (2 mm disc)

**Optimum**

\[ D_z = 0.15 \]
\[ c_i = 0.0057 \]
Optimum Reduced Strain Closure (1 mm disc)

**Optimum**

\[ k = 0.1 \]
\[ c_i = 0.0057 \]
Optimum Reduced Strain Closure (2 mm disc)

Optimum

\[ k = 0.1 \]
\[ c_I = 0.0057 \]
What we are working on now
Fatigue Test Sample

2.0 mm

1.0 mm

0.5 mm
Fatigue Test Sample
Optimum Reduce Strain Closure (Fatigue Test)

![Graph showing Orientation Factor vs Location Across Sample (mm) for Experimental A, Location A, Experimental B, and Location B.](image)
Long Glass Fibre Composites
Fibre Length Predictions

1 mm Plate 3.5 mm (Pellet fibre length input)
Fibre length distribution 0.15 mm from top surface
Average fibre length range up to 12.5 mm

1 mm Plate 3.5 mm (Nozzle fibre length input)
Fibre length distribution 0.15 mm from top surface
Average fibre length range up to 1.4 mm
Fibre Length Measurement System

Greyscale the image

Threshold

Thinning – 1 pixel thickness
Fibre Length Measurement System

Poly-line reduction – follows lines of pixels

Curve fit and line merge

Statistical output
Fibre Length Predictions

1 mm Plate 3.5 mm (Pellet fibre length input)
Fibre length distribution 0.15 mm from top surface
Average fibre length range up to 12.5 mm

1 mm Plate 3.5 mm (Nozzle fibre length input)
Fibre length distribution 0.15 mm from top surface
Average fibre length range up to 1.4 mm
Fibre Length Predictions

![Graph showing fibre length distribution with categories Experimental, Unmodified, Extrudate, and Sprue.](image_url)
Effect of the Nozzle

3.5 mm Nozzle

6.0 mm Nozzle
Warpage Predictions

30% Short Glass Fibre Reinforced Nylon
Maximum Warpage 6.2 mm

30% Long Glass Fibre Reinforced Nylon
Maximum Warpage 5.1 mm
Summary

- Midplane or Dual Domain analyses remain the best choice for fibre orientation predictions.
- The Folgar-Tucker model is incapable of predicting fibre orientation distribution for filled systems 10% and above.
- Modified version of the Folgar-Tucker model can achieve high degree of accuracy for parts with wall thicknesses up to 3 ~ 3.5 mm.
- RSC model offers some advantages over the older models but tuning of the k factor is required.
- Fibre length predictions are significantly enhanced by the use of nozzle exit fibre length profiles.
- Fibre breakage model can produce reasonable results.
Future

- Big push to extend the linear mechanical response of fibre filled materials to cover non-linear behaviour including fatigue
- Fibre length predictions must be linked to mechanical properties for accurate warpage predictions and responses to stress and strain fields (micro-mechanics)

- Micro-CT
Over to Ben
Autodesk Simulation Moldflow Insight for microinjection moulding

Dr Ben Whiteside
Director – Centre for Polymer Micro and Nano Technology
The Centre for Polymer MNT

Thanks to Max Babenko, Karthik Nair, John Sweeney, Gabriela Gonzalez-Castro
Micro Injection Moulding
Micromoulding definitions

- Products of sub-100mg mass
- Can be as low as 0.00001g
- Products with micron scale features and tolerances
- Nano-scale surface replication
Examples
Micromoulding process technology

14mm screw
Plunger injection
Servo drives
Fast response control
Switchover by pressure
So what’s the big deal?
Modelling considerations

To accurately model the process, we need to understand:

- Model geometry/Meshing strategies
- Material data
- Process/solver parameters
- Boundary conditions

Do these change for micromoulding geometries, or simply scale down?
Model geometry and meshing
Example 1

Volume = 0.34mm$^3$

Sprue/runner volume = 90.44mm$^3$

**Part % of shot weight = 0.4%**

Gate size = 200µm x 100µm
Mesh parameters

- Global edge length 0.05mm
- Merge tolerance 0.01mm
- Must be at least a factor of 5 lower
Mesh parameters

- 25810 elements in the product (<1%)
- 3512484 in the whole model
- Need variable mesh density to optimise the solution
Mesh refinement
Surface mesh density assignment
Remeshing results

- 97901 elements
- 10341 in product (>10%)
Example 2

Microneedle component

Feature height 600 µm

Base diameter: 300 µm

Product mass ~ 0.3 g
Meshing micro features

Target edge
0.025
0.040
0.080
0.150
0.250
Meshing micro features
Meshing summary

- Use mesh refinement tools wherever necessary to optimise the number of elements in the product or feature
- Scale down merge tolerance
- No real challenges imposed by micromoulding
Material data considerations
Most thermoplastics are pseudoplastic

Highly beneficial for micromoulding

But shear rates are especially high

High injection velocities/small features

What happens?

Theoretical wall shear rate vs gate radius for maximum flow rate of Microsystem 50

Gate radius 100µm, wall shear rate >10 000 000 s⁻¹!
Material database viscosity data

- The AMI 2014 material database is comprehensive
- Measurements performed to shear rates $\sim 10^5 \text{s}^{-1}$
- How can we verify the power law behaviour still holds?
High shear rheometry

- Evolution of capillary rheometry
- Convert a high speed injection moulding machine
- High injection speed (780mm/s) and pressures (2800Bar)
- Allows testing of materials to wall shear rates in excess of $10,000,000 \text{s}^{-1}$
High shear viscosity data
Material data checks

- Check your shear rate values
- Make sure you are within the database range
- Extrapolation is dangerous!
Process/solver parameters
Process dynamics

- Component is the last 0.4% of the cavity filling
- The volume of the part corresponds with a plunger displacement of just 0.0175mm
- At an injection velocity of 400mm/s, the part will fill in just 40µs!
- Products will often fill under hold pressure
Process dynamics

- Features form just 0.13% of the total cavity volume
- Wall slip at the base of the microfeatures can occur causing the needles to fill at the end of fill
- Products can fill under hold pressure
Solver parameters

- Lower max volume for time step
  - Important in case of large sprue/part ratio

- Simulate inertia
  - Better jetting performance

- Wall slip?
Simulate inertia effect results

Simulate inertia off

Simulate inertia on
Boundary conditions
Micromoulded product surface area

- The surface area to volume ratio increases as part dimensions decrease.
- The interface between melt and mould surface becomes much more significant in micromoulding.
- Low thermal energy (heat) and large contact areas cause cooling in fractions of a second.

The variation of Surface Area / Volume as a function of length for some solids.
Section analysis – microstructure control

Polarised light microscopy of micro-tomed sections perpendicular to the filling axis

The proximity of the bulk of the material in the moulding to the cavity surface allows us to significantly influence internal structures.
Boundary conditions

- The melt/mould interface is more significant for micromoulding than conventional IM
- We need to be able to accurately characterise heat flow across this boundary to generate a meaningful result
ASMI 2014 allows specification of HTC which describes the ability for heat to flow across the melt/mould interface.

- A higher value indicates easier heat flow and more rapid cooling.
- Determined from conventional IM experimental measurements.
- Suitable for micromoulding?
What influences HTC?

Thermal contact resistance (TCR) is defined as the resistance to heat flow between two bodies in contact. It depends primarily on the contact area, which itself must be a function of:

- Mould surface topography
- Pressure
- Material properties (viscosity, conductivity etc.)
- Surface energy
- Interfacial fluids
Direct measurement of cooling behaviour

- Ultra high speed, high sensitivity IR camera
- Indium antimonide (InSb) IRFPA detector.
- Spectral Range: 1.5 – 5 μm.
- Sensitivity: 20 mK, capture difference of 0.02 °C.
- Full frame size: 320 x 256 pixels.
- User adjustable frame size in 16 by 2 pixels with the frame rate up to 30 KHz.
- Integration time: can be adjusted in nanosecond increments in the range of 100 ns to full frame.
Experimental arrangement

- DAQ
- High speed thermal imaging camera
- p-T sensor
- Cavity
- Sapphire window
- Mould moving part
- Runner
- Injection plunger
- Injection nozzle
- Mould fixed part
- Micro positioning stage
- Right angle mirror
Calibration

- System calibrated in situ
- Set mould temperature
- Inject polymer
- Allow to stabilise for 15 mins
- Record camera values
- Verify melt T with p/T sensor
- Repeat over the range of 50 °C to 200 °C
- Create calibration curve
Calibration curves

Calibration Curve for Sabic Vestolen A 6060R (HDPE)

\[ y = 64.49 \ln(x) - 356.9 \]

\[ R^2 = 0.999 \]

Temperature (Deg C) vs Camera Value
Initial camera data

- Optically flat (<1nm Ra) Sapphire surface
- HDPE 1% Carbon Black
- 200 mm/s injection velocity
- 200 C Melt Temperature
- 50 C mould temperature
- 500 Bar hold pressure

320 x 256 px
0.1ms exp
385 fps

160 x 160 px
0.1ms exp
1000 fps
Surface Measurement

- An elevated temperature at the flow front suggests we are recording a surface measurement due to fountain flow.
Melt temperature effects - area measurements

180 ºC

200 ºC

220 ºC
Process data curves

- Injection pressure
- Cavity pressure
- IR temp
- P/T temp
Process data curves

- Injection pressure
- Cavity pressure
- IR temp
- P/T temp
Process data curves – latent heat of crystallisation

Cooling curves for Melt T 240, Mould T 80, Injection speed 100 mm/s

Polystyrene (amorphous)

Polypropylene (semi-crystalline)
HTC modelling

- ABAQUS model simulates contact resistance as a finite layer with no specific heat capacity
- Assume symmetry and model temperature decay through the sapphire window
- Heat removed from external face of window through convection
HTC modelling results

- Acquire temperature profile for a node on the melt side of the HTC boundary.

- Results suggest a value of approximately 3300 W m\(^{-2}\) C\(^{-1}\) for the experimental arrangement.

- This is lower than the ASMI 2014 default, but could be due to the very flat sapphire surface.

- How does surface roughness affect the HTC value?
Surface roughness influence

- Scan real tool surfaces
- Recreate in sapphire using FIB
- Laser machined samples

<table>
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<th>Material</th>
<th>Thermal Conductivity (W/m.K)</th>
<th>Specific Heat (J/kgK)</th>
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<td>Sapphire window</td>
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<td>750</td>
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Cooling Graph

- HDPE 2.5% Carbon Black
- Two surfaces:
  - 2 nm Ra
  - 320 nm Ra
- 180 C Melt Temperature
- 60 C mould temperature
- 650 Bar hold pressure
Roughness Effects on Cooling

- Initially, the rougher surface cools faster
- Once the injection pressure decays, the cooling curves cross
- Reheat is seen at the rougher surface
HTC studies in ASMI 2014
Model 1 – flat component
Model 1 – flat component
Model 2 – microneedle component

- Each row of needle elements assigned increasing HTC value
  - 1000 W m\(^{-2}\) C\(^{-1}\)
  - 2000 W m\(^{-2}\) C\(^{-1}\)
  - 4000 W m\(^{-2}\) C\(^{-1}\)
  - 8000 W m\(^{-2}\) C\(^{-1}\)
  - 16000 W m\(^{-2}\) C\(^{-1}\)
Microneedle model
Microneedle results – temperature profile

- Clear that high HTC significantly affects cooling and even causes a short shot here
Microneedle results – unfilled volume
Microneedle results – unfilled volume
Results vs experimental measurements

- Measured needle length 550 µm
- Suggests a value of 8000 W m\(^{-2}\) C\(^{-1}\)
- Higher value due to rougher surface from manufacturing process (Micro Electro Discharge Machining)
- Need to consider surface finishes when assigning HTC values

<table>
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<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
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<td>570 µm</td>
<td>550 µm</td>
<td>520 µm</td>
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Summary

- There are a number of aspects which should be considered when using ASMI 2014 for micromoulding applications
- Heat Transfer Coefficient (HTC) is a crucial parameter for predicting filling behaviour of microfeatures
- We have developed a system to measure surface temperatures directly for HTC measurement
- HTC is dependent on mould surface roughness and pressure
- We are working to build empirical models of HTC
Thank you