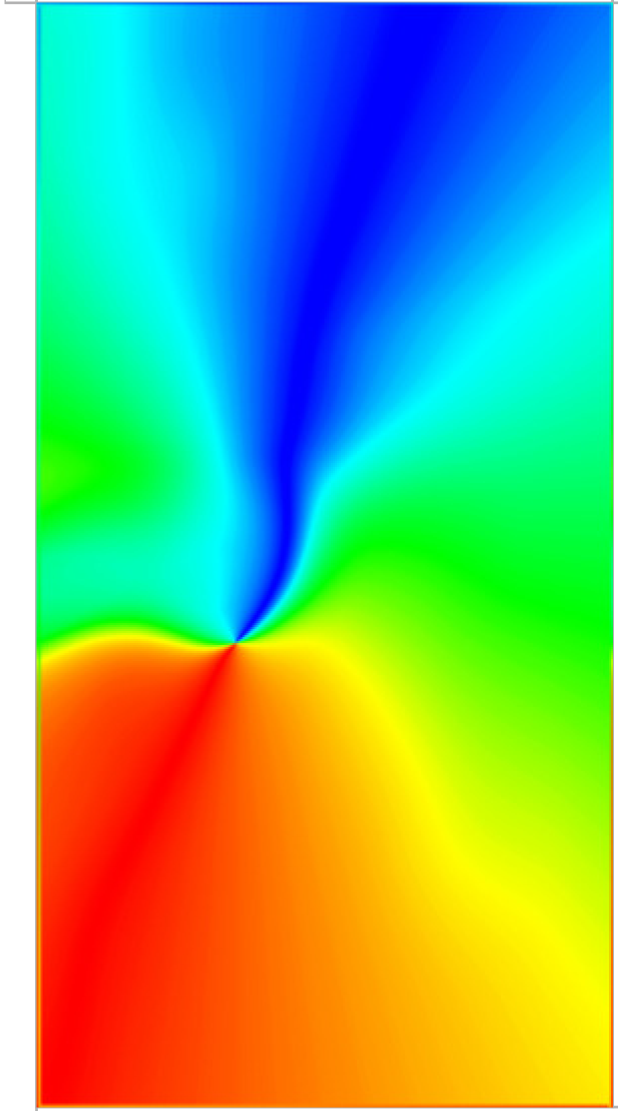


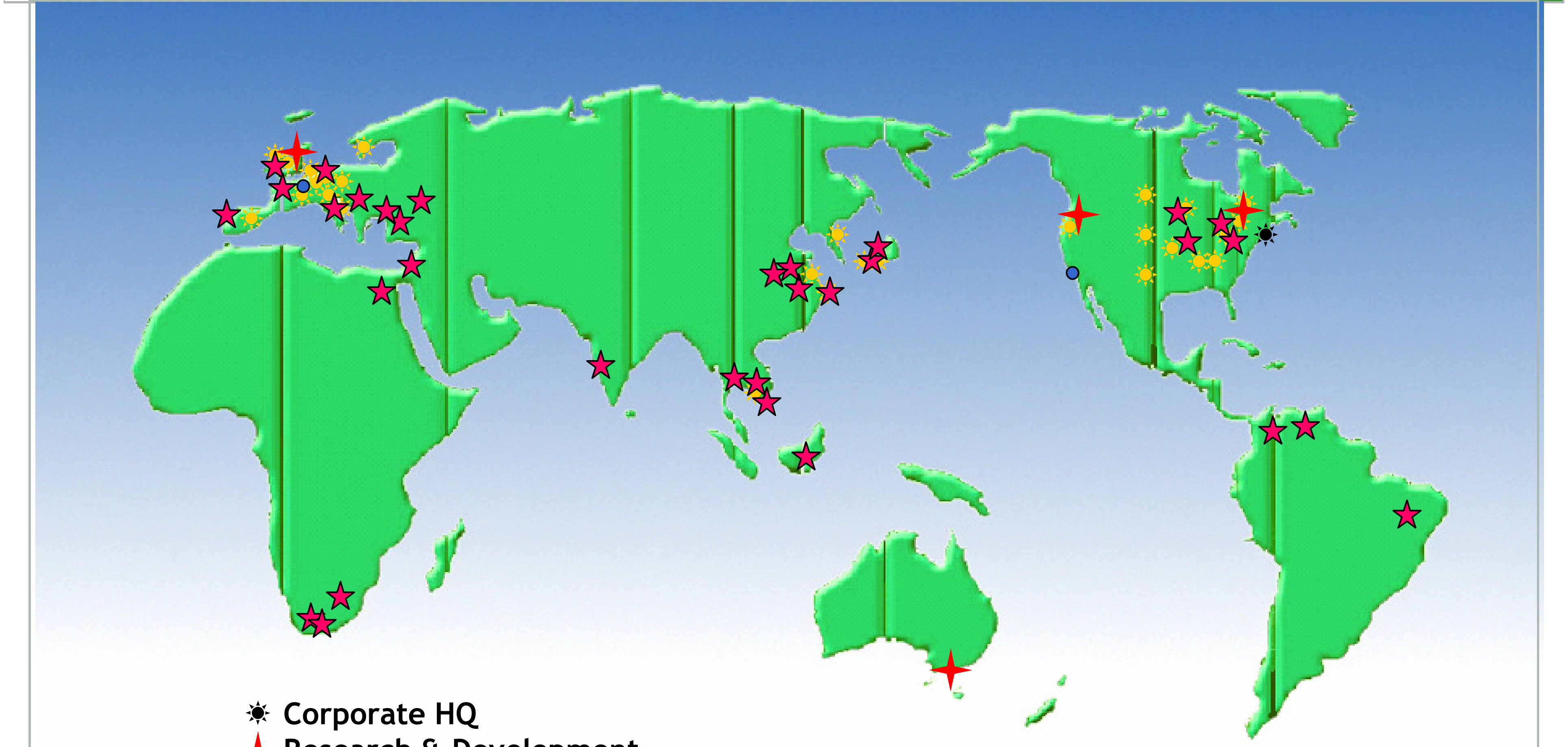
Moldflow Technology

Recent Developments & Data Requirements

NPL March 12 2008

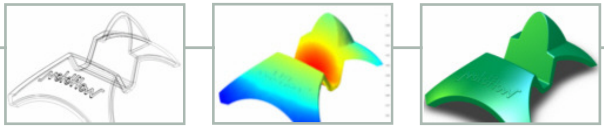
Who we are

Global Operations



✹ Corporate HQ
✦ Research & Development
☀ Direct Sales & Support
● Manufacturing Center

★ Distributors & Mfg's Reps



moldflow®
plastics made perfect™

Moldflow Products – Core Modules

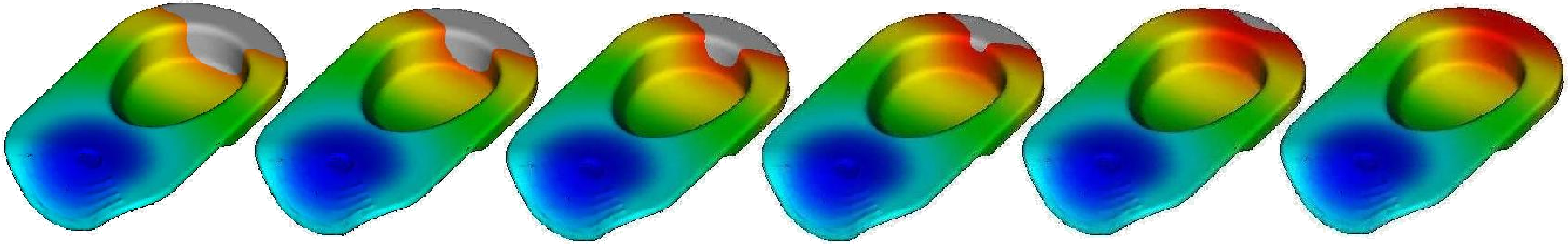
- Injection moulding:
  - MPI/Flow
  - MPI/Cool
  - MPI/Warp

Other Simulation Applications

- Design of Experiments
- Mould core deflection
- 2-shot, Co-injection
- Gas assist
- Injection-compression
- Insert overmoulding
- Micromoulding
- Rubbers & Thermosets, incl warpage
- Liquid Crystal Polymers
- MuCell
- Birefringence
- Interface to FEA (structural loading)

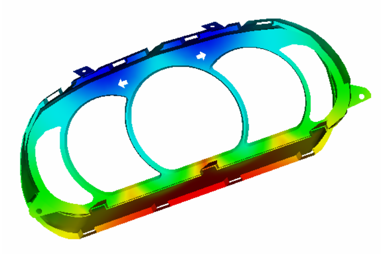
Fill Pattern Verification

Moldflow prediction for flow pattern near end of fill



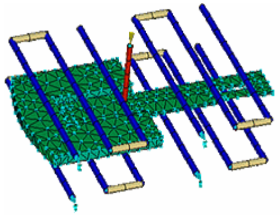
Short shots to show actual flow pattern near end of fill

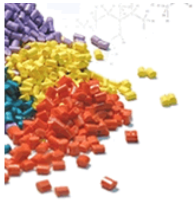
Factors that effect accuracy



- Solver Technology

- Component Modeling





- Material Data

- Process Conditions

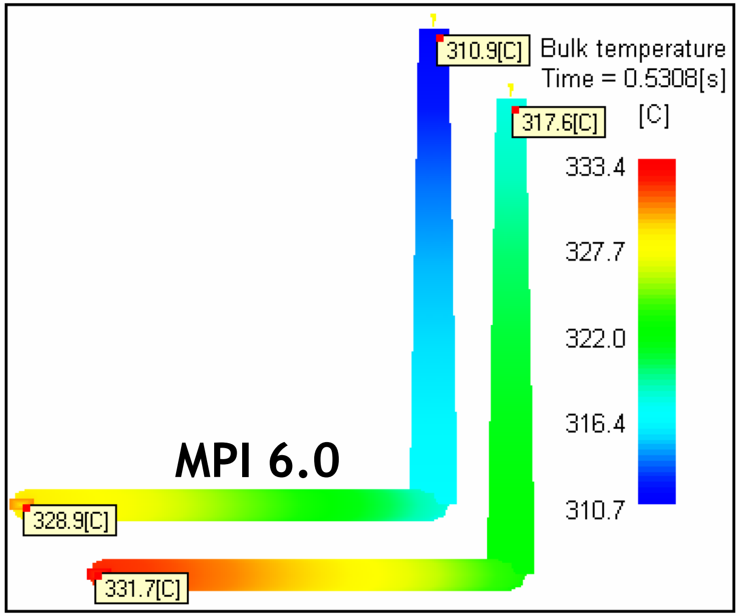
Solver Improvements

- Gravity effects
  - For low viscosity materials

- Polymer jetting flow
  - Causes flow marks on surface
  - Polymer jet buckles, touches mould and cools

Compressive Heating Added

- Compressive heating added to energy equation for fluid flow
- Melt temperature will increase as the material gets compressed
- Generally pressures will be 4% to 5% lower than before



MPI 6.1

Measured Melt-Mould Heat Transfer Coefficient

- Thermal contact resistance measured during molding cycle
- HTC = 1/TCR
- Delaunay, Le Bot et al. Poly.Eng.Sci 40 (1682-1691)

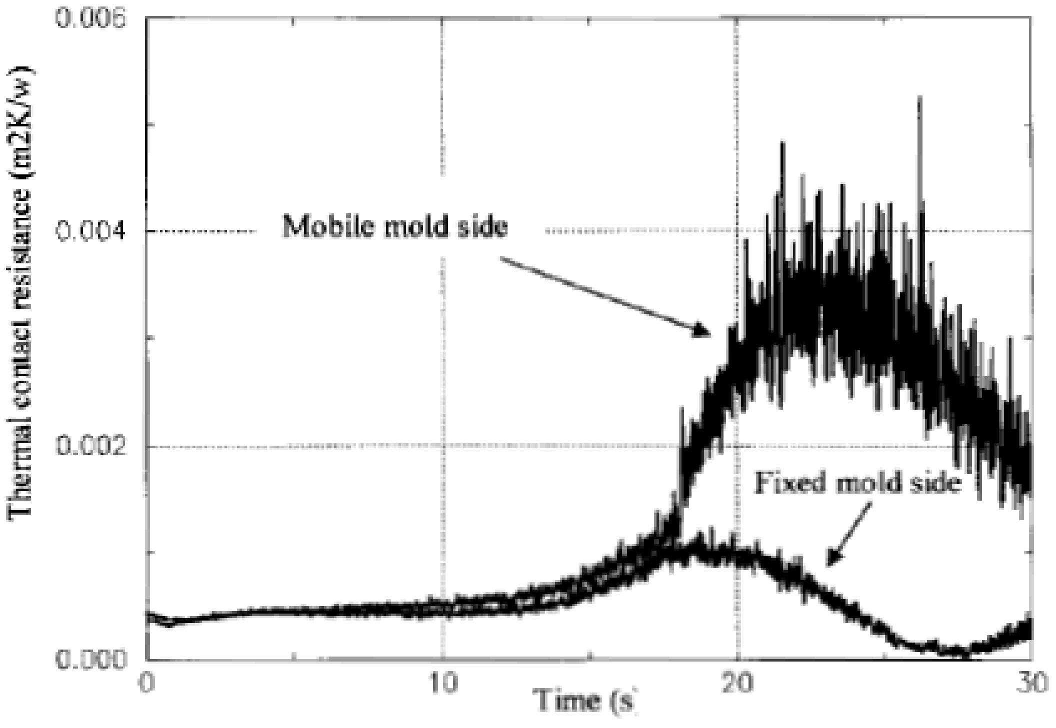
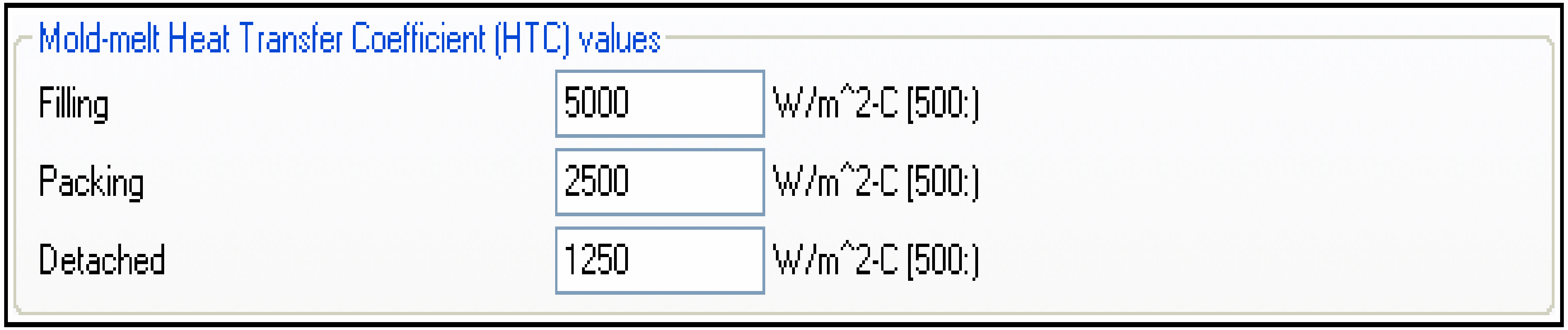


Fig. 10. Thermal contact resistance evolution on both interfaces.

3-Stage Heat Transfer Coefficient (HTC)

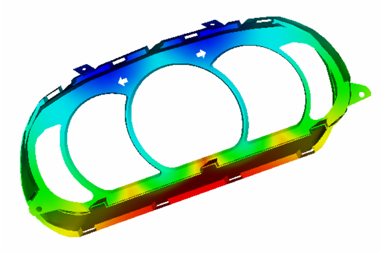
- Flow Solvers now use 3-stage HTC
- Defaults
  - 5000 W/m^2 Filling
  - 2500 W/m^2 Packing
  - 1250 W/m^2 Detached (pressure = 0)



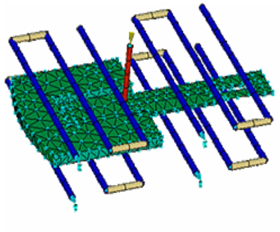
Mold-melt Heat Transfer Coefficient (HTC) values

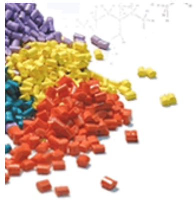
Filling	5000	W/m^2-C [500:)
Packing	2500	W/m^2-C [500:)
Detached	1250	W/m^2-C [500:)

Factors that effect accuracy



- Solver Technology
- Component Modeling





- Material Data
- Process Conditions

Test Resources

Melbourne, Australia

- Visco-elastic
- Thermoset Chemo-Rheometry
- Shrinkage for fibre materials
- No flow temperature for LCP’s

Melbourne + Ithaca, NY

- Injection Molding Rheometry
- Shrinkage testing
- Pressure Volume Temperature
- Thermal conductivity
- Differential Scanning Calorimetry
- Solid Density
- Shrinkage Measurements
- Moisture Measurement
- Material Conditioners
- Environmental Control

Ithaca, NY, US

- Mechanical Properties
- Twin Bore Capillary Rheometer
- Shrinkage for non-fibre materials
- pvT for Thermosets

International Standards

Injection Molding Rheology:

- ASTM D5422 Standard Test Method for Measurement of Thermoplastic Materials by Screw-Extrusion Capillary Rheometer
- ASTM D3835 Standard Test Method for Determination of Properties of Polymeric Materials by Means of a Capillary Rheometer
- ISO-11443 Plastics - Determination of the fluidity of plastics using capillary and slit-die rheometers

Thermal Conductivity:

- ASTM D5930, Standard Test Method for Thermal Conductivity of Plastics by Means of a Transient Line-Source Technique

Differential Scanning Calorimetry:

- ASTM E1269 Determination of Specific Heat Capacity by Differential Scanning Calorimeter
- ASTM D3417 Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimeter
- ASTM D3418 Transition Temperatures of Polymers by Differential Scanning Calorimetry

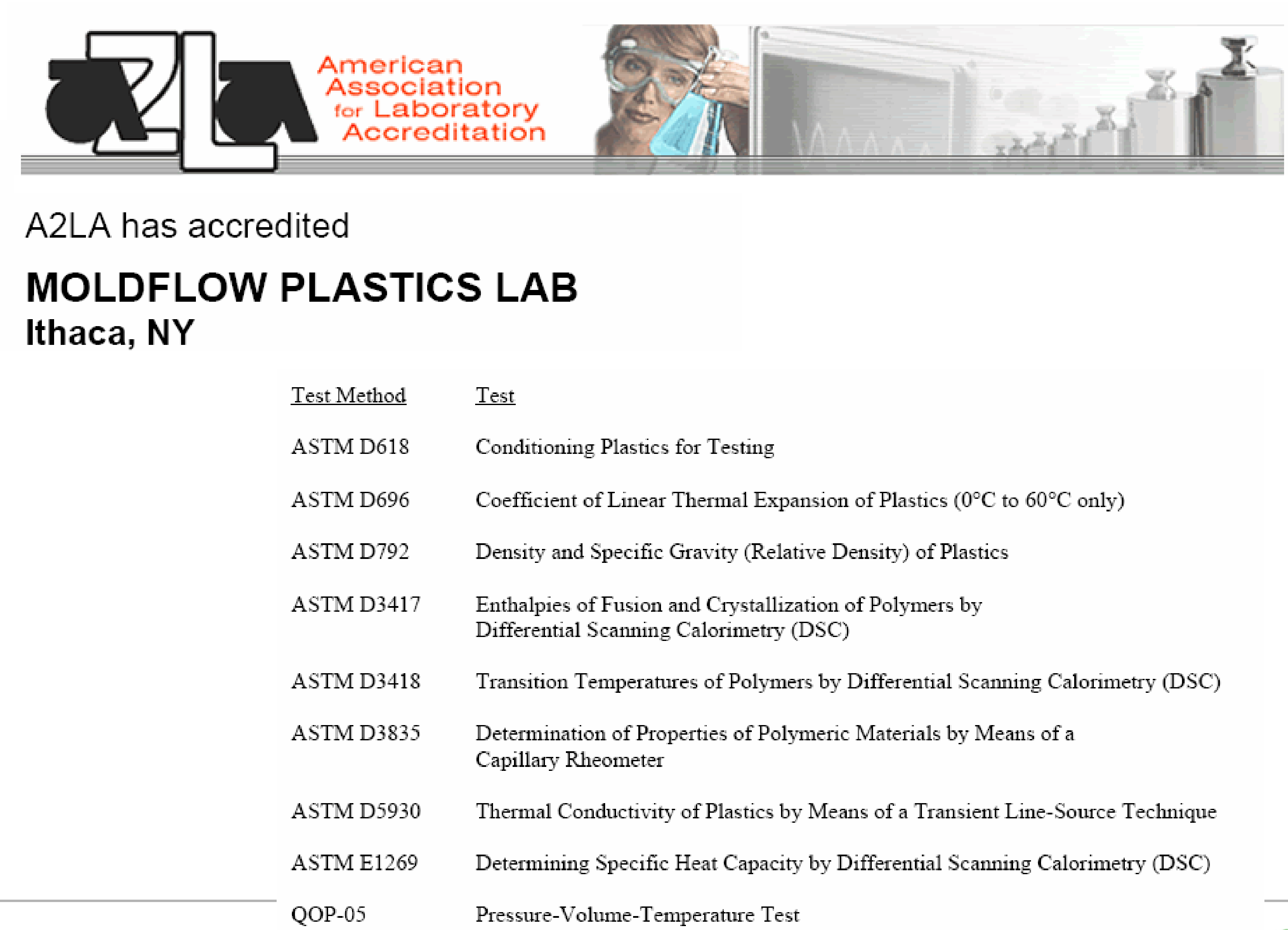
Mechanical Properties:

- ASTM D-638 Tensile Properties of Plastics
- ASTM E-132 Poisson’s Ratio at Room Temperature

Coefficient of Thermal Expansion:

- ASTM D-696 Coefficient of Linear Thermal Expansion of Plastics

American Association for Laboratory Accreditation

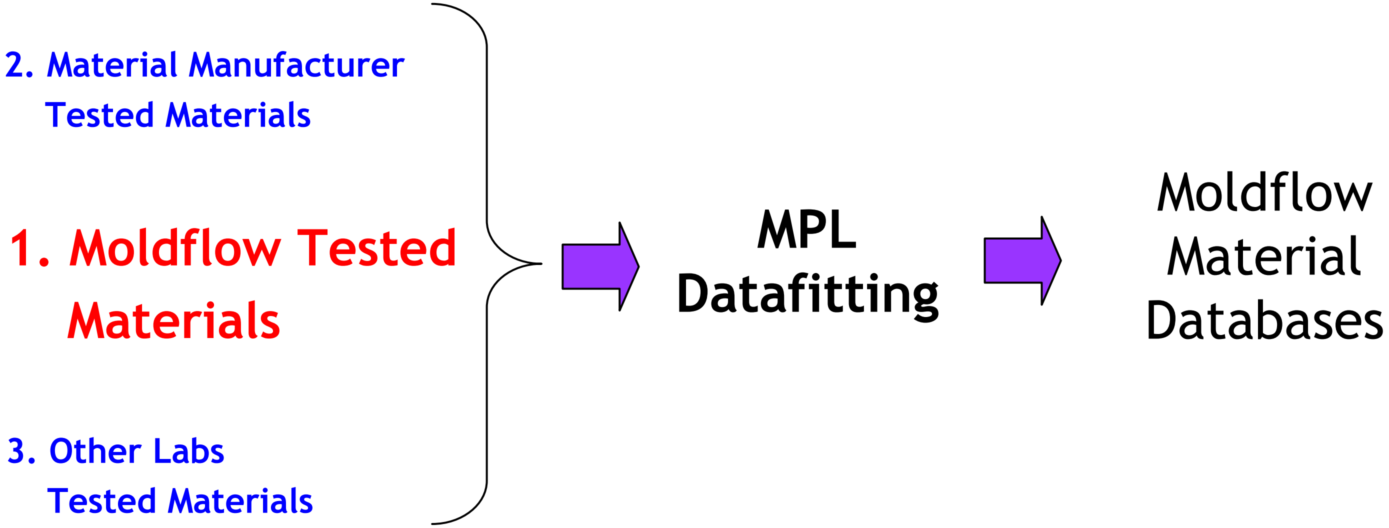


A2LA has accredited

MOLDFLOW PLASTICS LAB
Ithaca, NY

Test Method	Test
ASTM D618	Conditioning Plastics for Testing
ASTM D696	Coefficient of Linear Thermal Expansion of Plastics (0°C to 60°C only)
ASTM D792	Density and Specific Gravity (Relative Density) of Plastics
ASTM D3417	Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry (DSC)
ASTM D3418	Transition Temperatures of Polymers by Differential Scanning Calorimetry (DSC)
ASTM D3835	Determination of Properties of Polymeric Materials by Means of a Capillary Rheometer
ASTM D5930	Thermal Conductivity of Plastics by Means of a Transient Line-Source Technique
ASTM E1269	Determining Specific Heat Capacity by Differential Scanning Calorimetry (DSC)
QOP-05	Pressure-Volume-Temperature Test

Material Data Source



2. Material Manufacturer
   Tested Materials

1. Moldflow Tested Materials

3. Other Labs
   Tested Materials

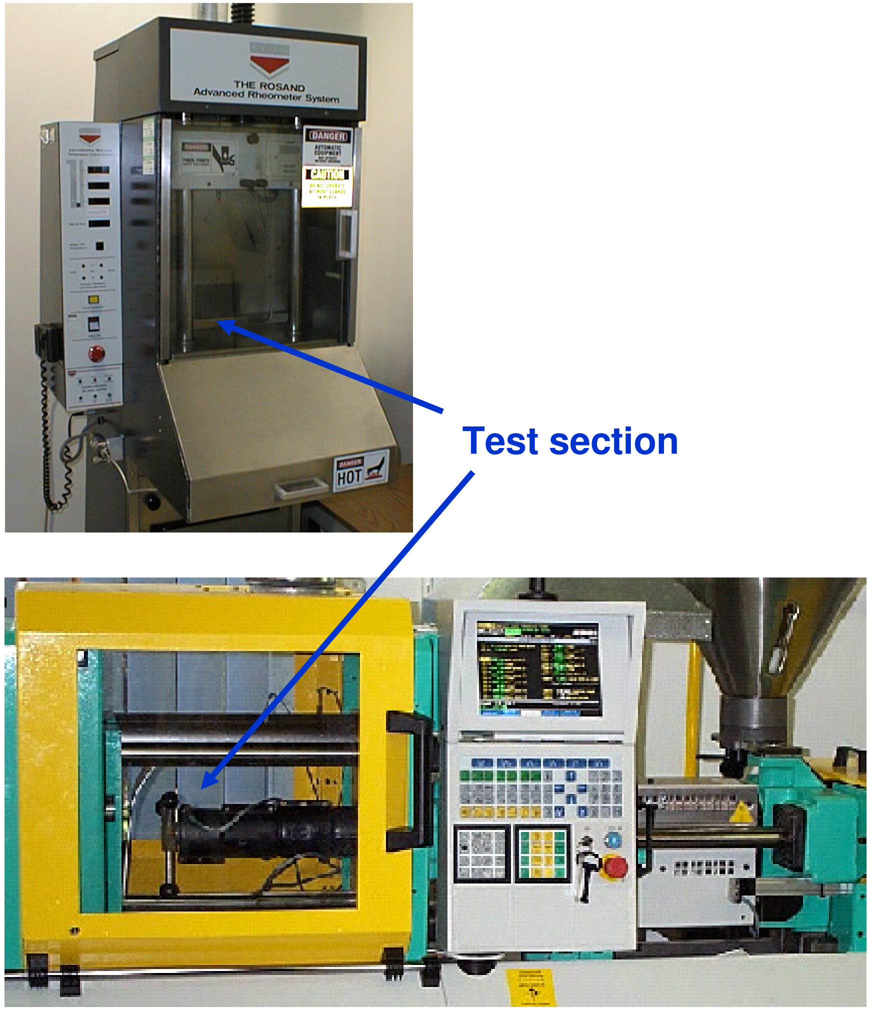
MPL Datafitting

Moldflow
Material
Databases

8000 Materials

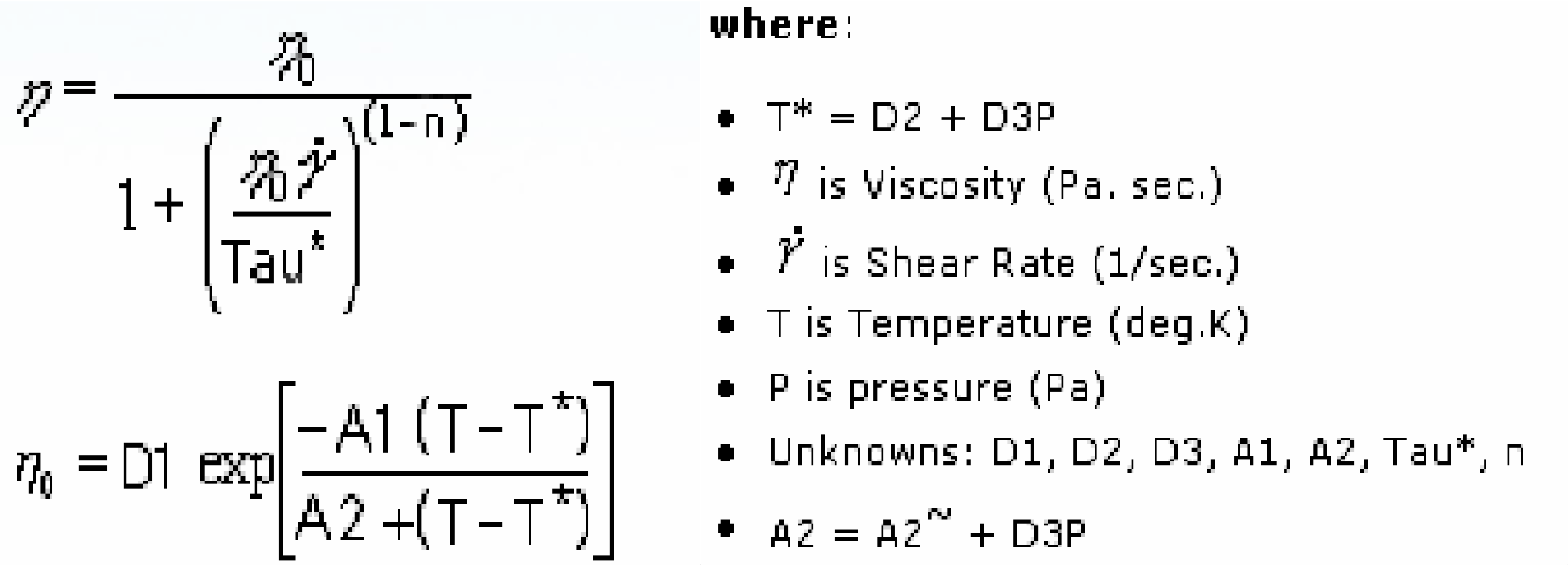
Capillary rheometers

- Rosand RH-7
  - Classic method (offline)
  - Reservoir/Plunger
  - Long residence times
- IMR
  - Moulding machine method (online)
  - Charge/Shutoff Screw
  - Short residence times
  - Suitable for high performance materials



Modified Cross-WLF model

- Cross model captures the shear rate sensitivity of most material families
- WLF equation captures exponential-hyperbolic temperature sensitivity depending on the magnitude of T-T*



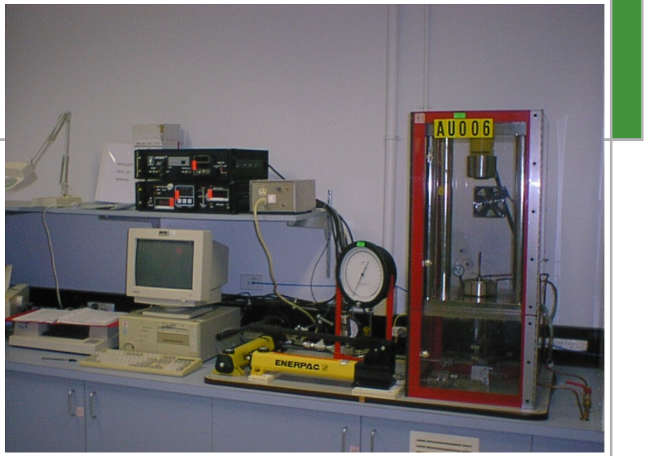
$$\eta = \frac{\eta_0}{1+\left(\frac{\eta_0 \dot{\gamma}}{Tau^*}\right)^{(1-n)}}$$

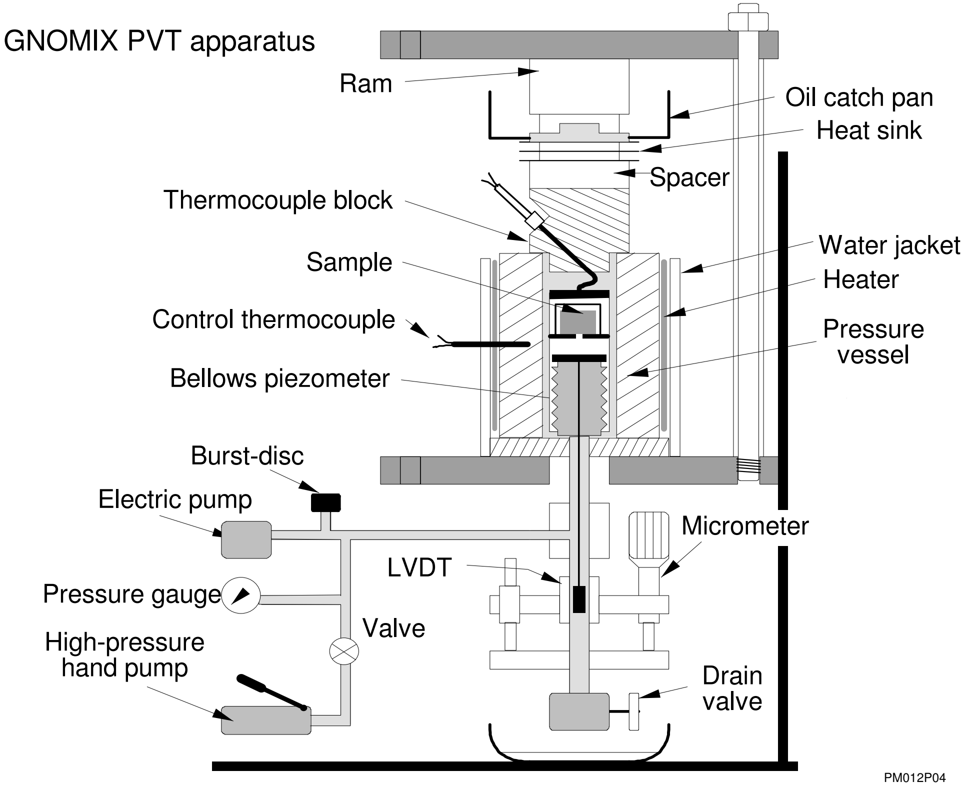
$$\eta_0 = D1 \; \exp\left[\frac{-A1\,(T-T^*)}{A2+(T-T^*)}\right]$$

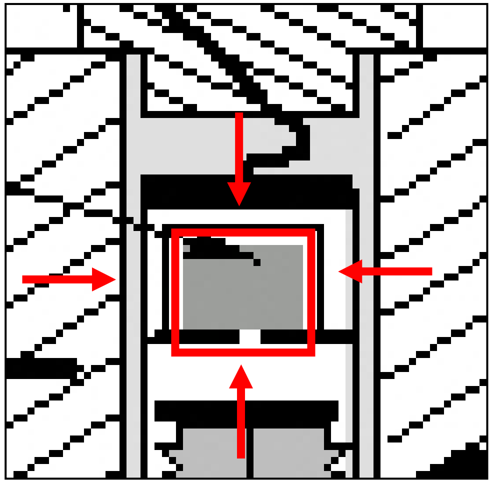
where:

- $T^* = D2 + D3P$
- η is Viscosity (Pa. sec.)
- $\dot{\gamma}$ is Shear Rate (1/sec.)
- T is Temperature (deg.K)
- P is pressure (Pa)
- Unknowns: D1, D2, D3, A1, A2, Tau*, n
- $A2 = A2^{\sim} + D3P$

Gnomix - PVT

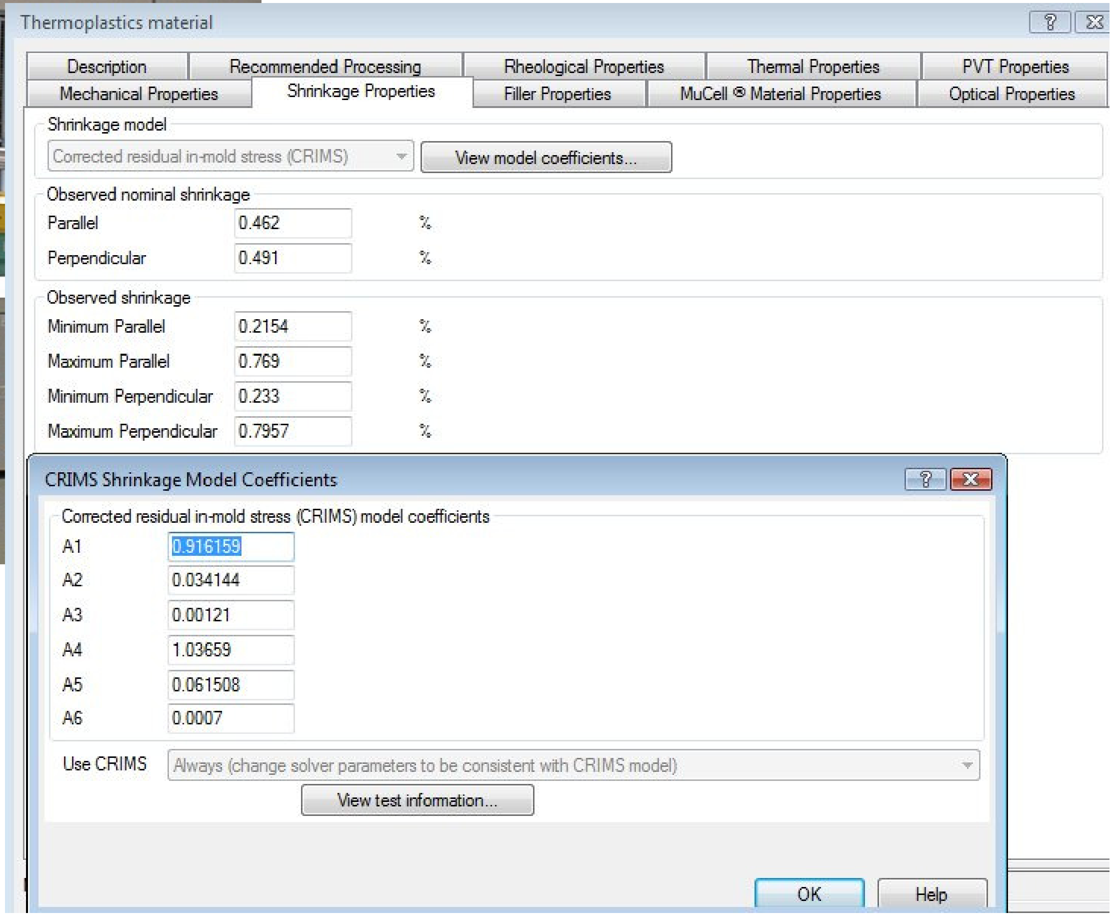






Confining fluid (mercury) ensures the test material experiences isobaric conditions.

Shrinkage Testing & Warpage Coefficients



Shrinkage model: Corrected residual in-mold stress (CRIMS)

Observed nominal shrinkage
Parallel 0.462 %
Perpendicular 0.491 %

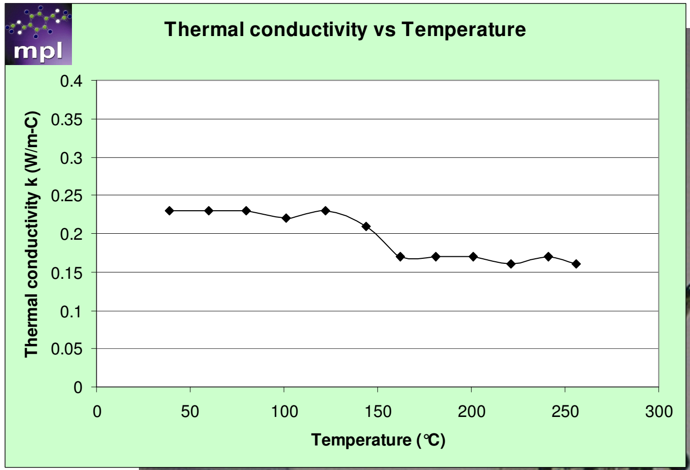
Observed shrinkage
Minimum Parallel 0.2154 %
Maximum Parallel 0.769 %
Minimum Perpendicular 0.233 %
Maximum Perpendicular 0.7957 %

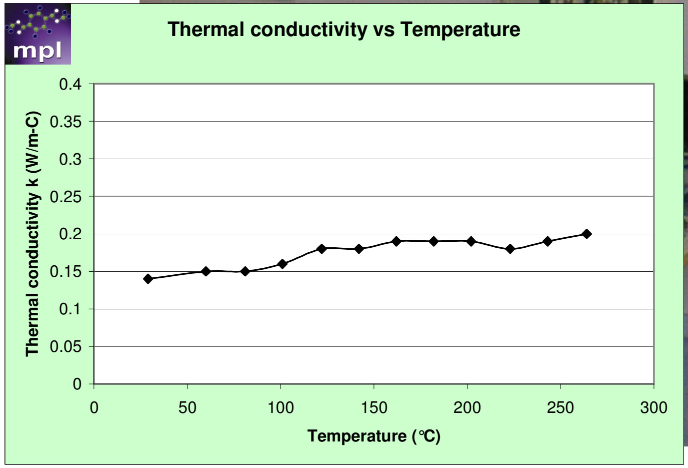
Corrected residual in-mold stress (CRIMS) model coefficients
A1 0.916159
A2 0.034144
A3 0.00121
A4 1.03659
A5 0.061508
A6 0.0007

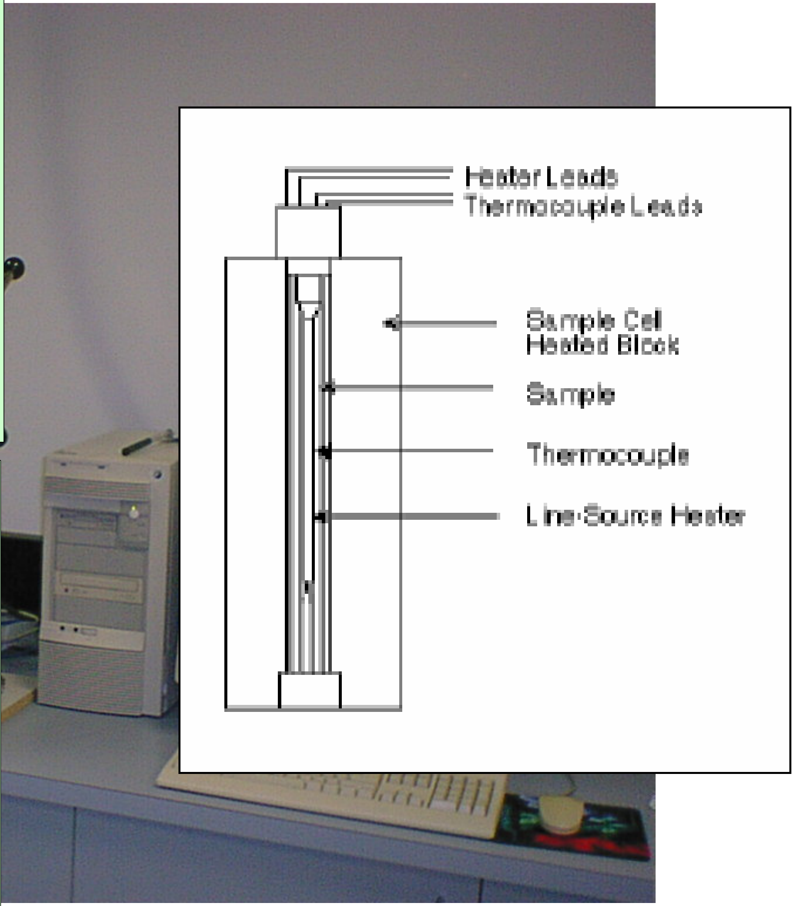
Use CRIMS: Always (change solver parameters to be consistent with CRIMS model)

Shrinkage test facilities – ensures accurate shrinkage predictions

Thermal Conductivity K-System II

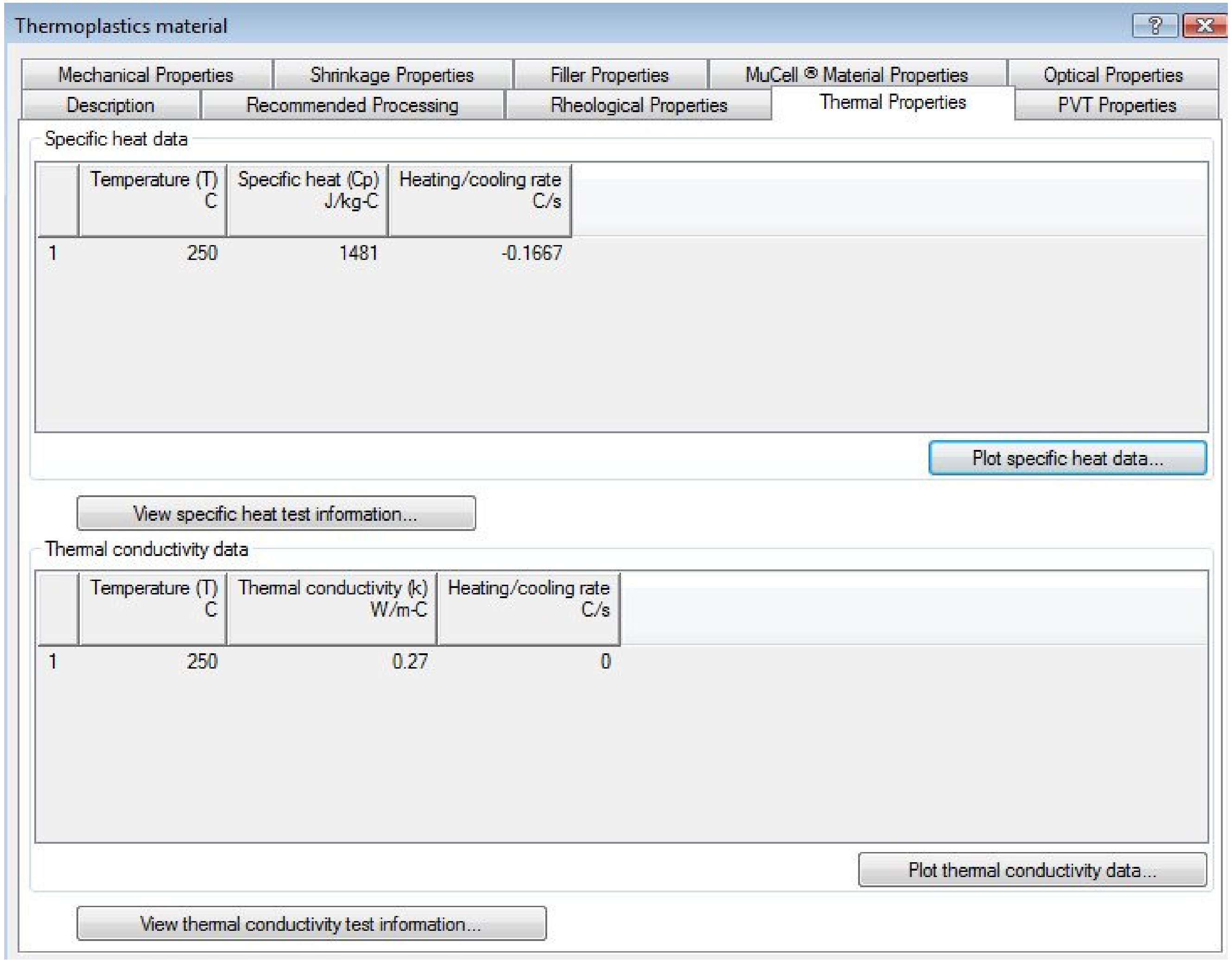






Multi-point thermal conductivity data

Single Point Thermal Data



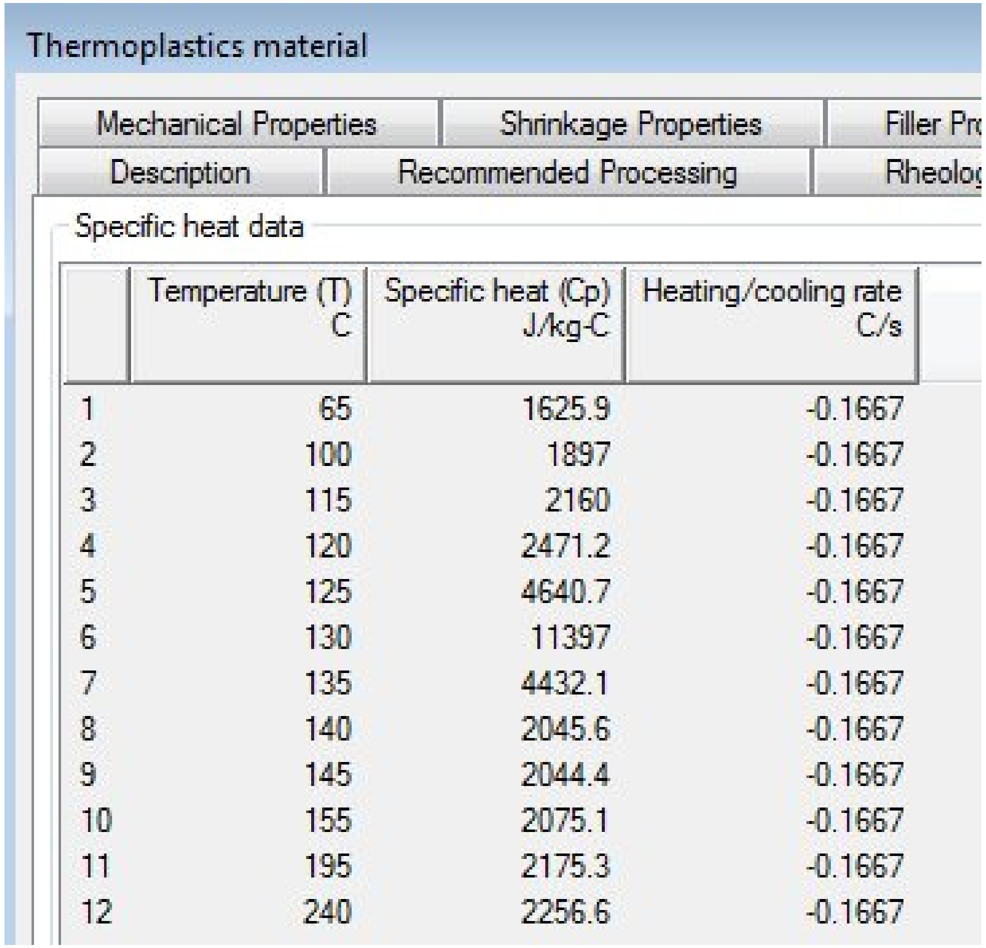
Specific heat data

	Temperature (T) C	Specific heat (Cp) J/kg-C	Heating/cooling rate C/s
1	250	1481	-0.1667

Thermal conductivity data

	Temperature (T) C	Thermal conductivity (k) W/m-C	Heating/cooling rate C/s
1	250	0.27	0

Multi Point Thermal Data

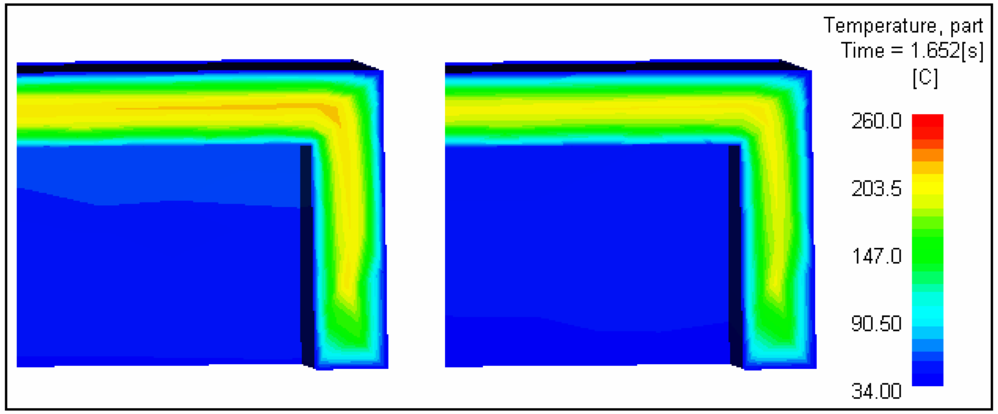


Specific heat data

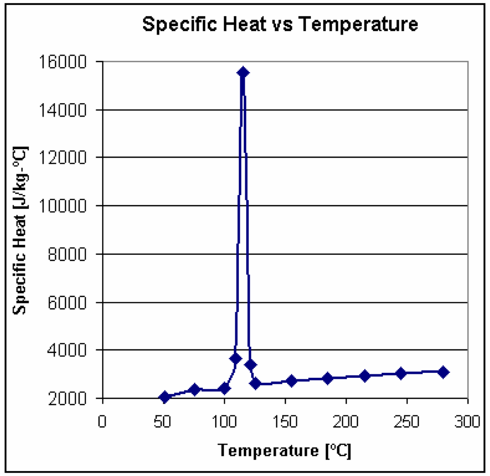
	Temperature (T) C	Specific heat (Cp) J/kg-C	Heating/cooling rate C/s
1	65	1625.9	-0.1667
2	100	1897	-0.1667
3	115	2160	-0.1667
4	120	2471.2	-0.1667
5	125	4640.7	-0.1667
6	130	11397	-0.1667
7	135	4432.1	-0.1667
8	140	2045.6	-0.1667
9	145	2044.4	-0.1667
10	155	2075.1	-0.1667
11	195	2175.3	-0.1667
12	240	2256.6	-0.1667

Cooling Uses Multi-Point Thermal Data

- Now the cooling solver uses multi-point thermal data for heat flux calculations in the part
- Results typically will have only a subtle change

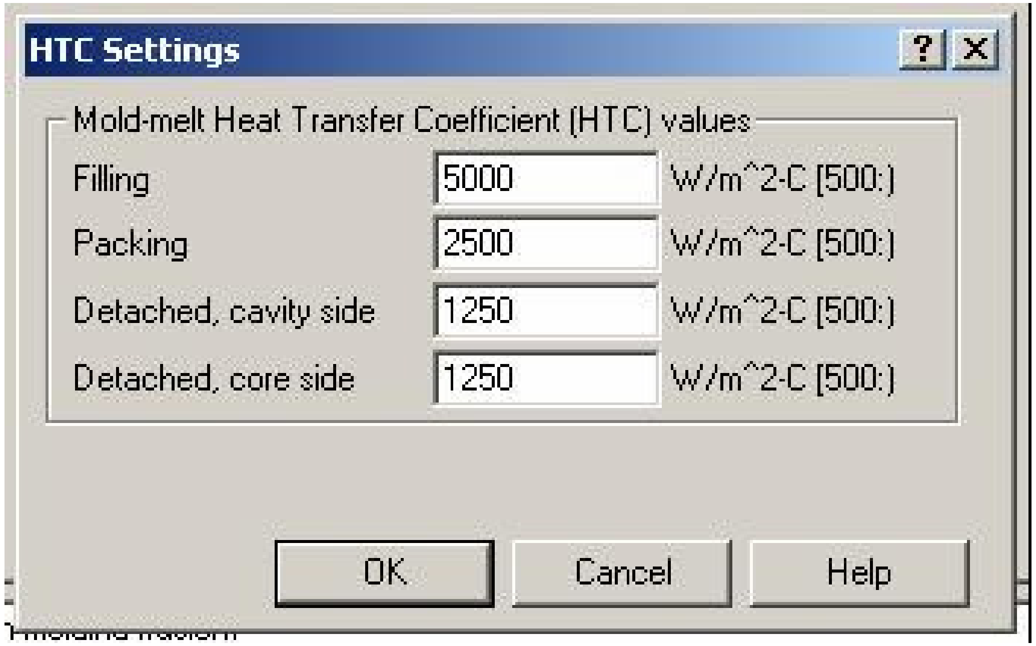


Single point **Multi point**



Improving Simulation for LCP’s

- Correct selection of Melt-Mold Heat Transfer Coefficient is significant in LCP materials



HTC Settings

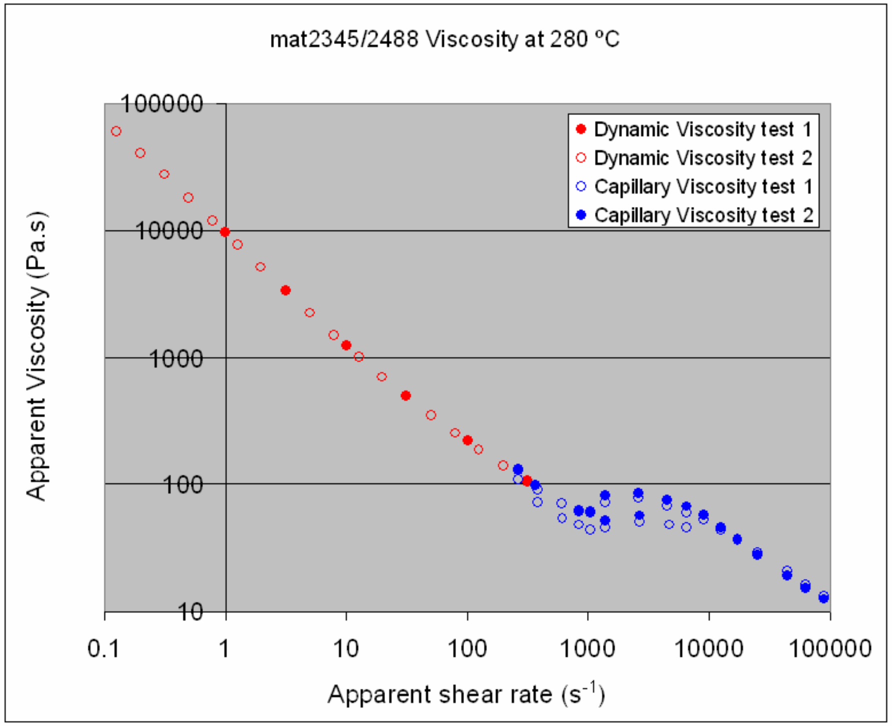
Mold-melt Heat Transfer Coefficient (HTC) values

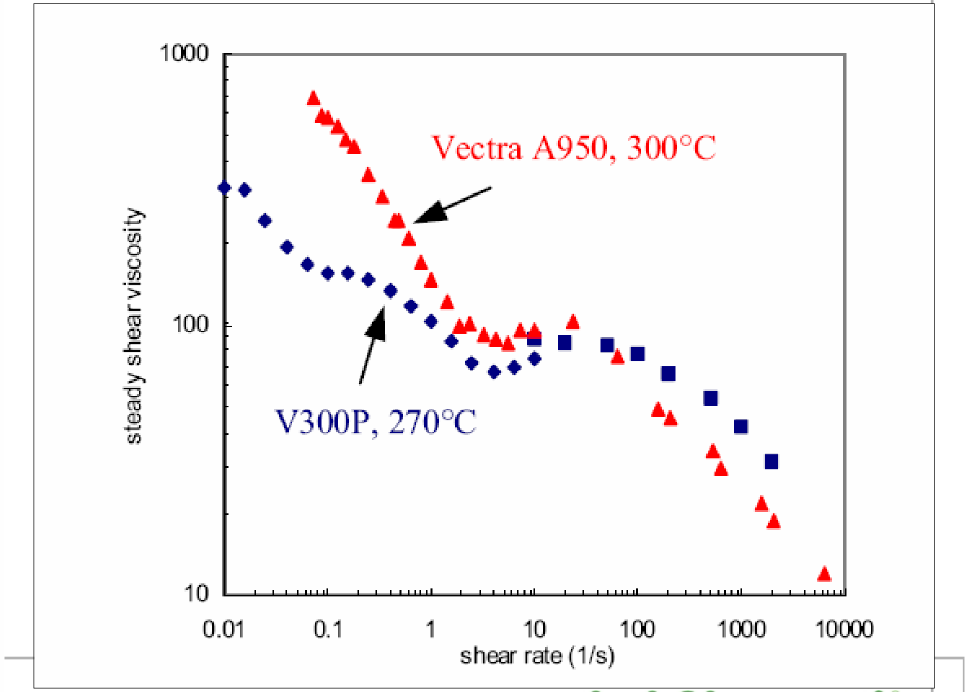
Filling	5000	W/m^2-C [500:)
Packing	2500	W/m^2-C [500:)
Detached, cavity side	1250	W/m^2-C [500:)
Detached, core side	1250	W/m^2-C [500:)

LCP – Unusual behaviour at low rates

- LCP – “three region” flow

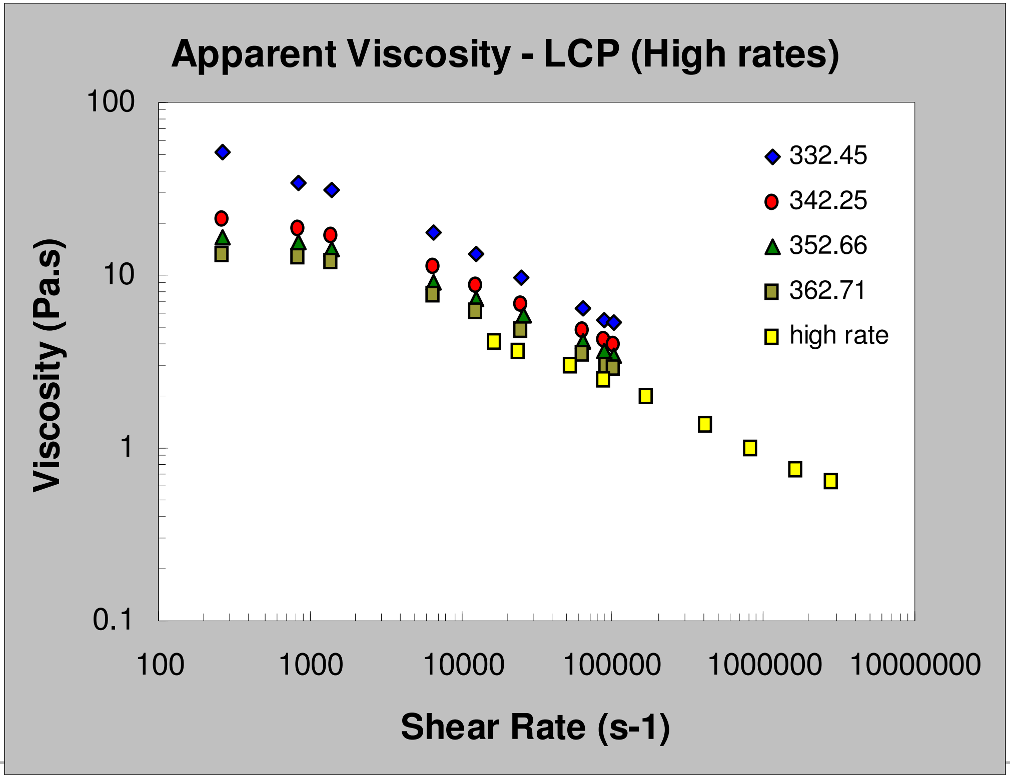
  Guo, T., Harrison, G.M., and Ogale, A.A., "Rheology and microstructure of thermotropic liquid crystalline polyesters," Antec (2001).



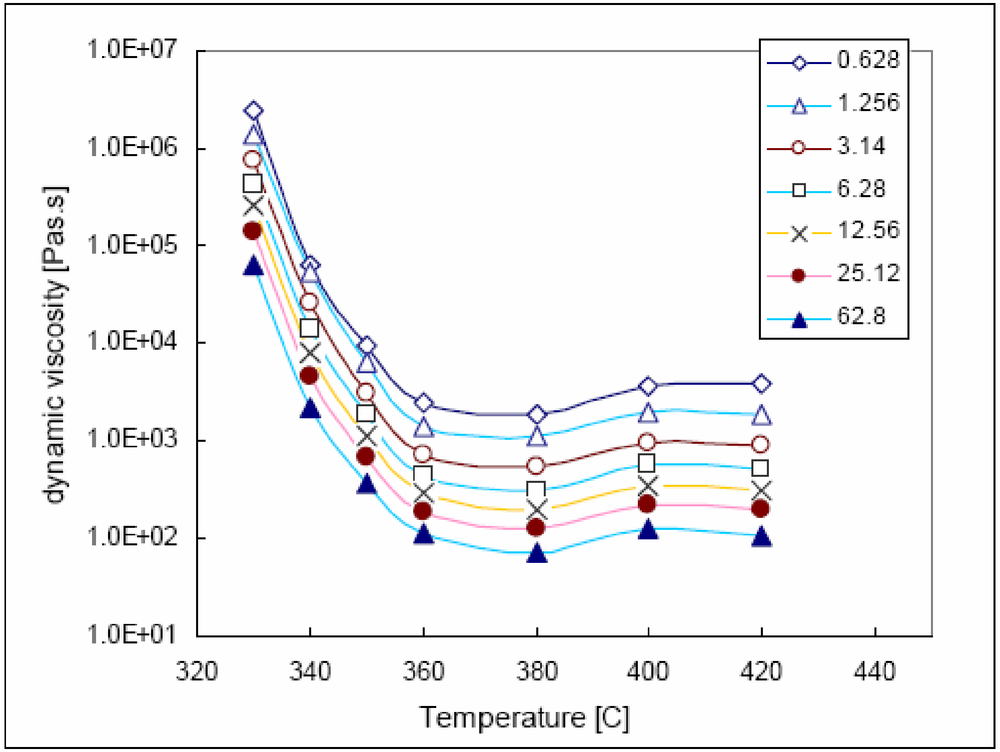


LCP – Unusual behaviour at high rates

- There is suggestion of a plateau in the data at shear rates > 1,000,000/s



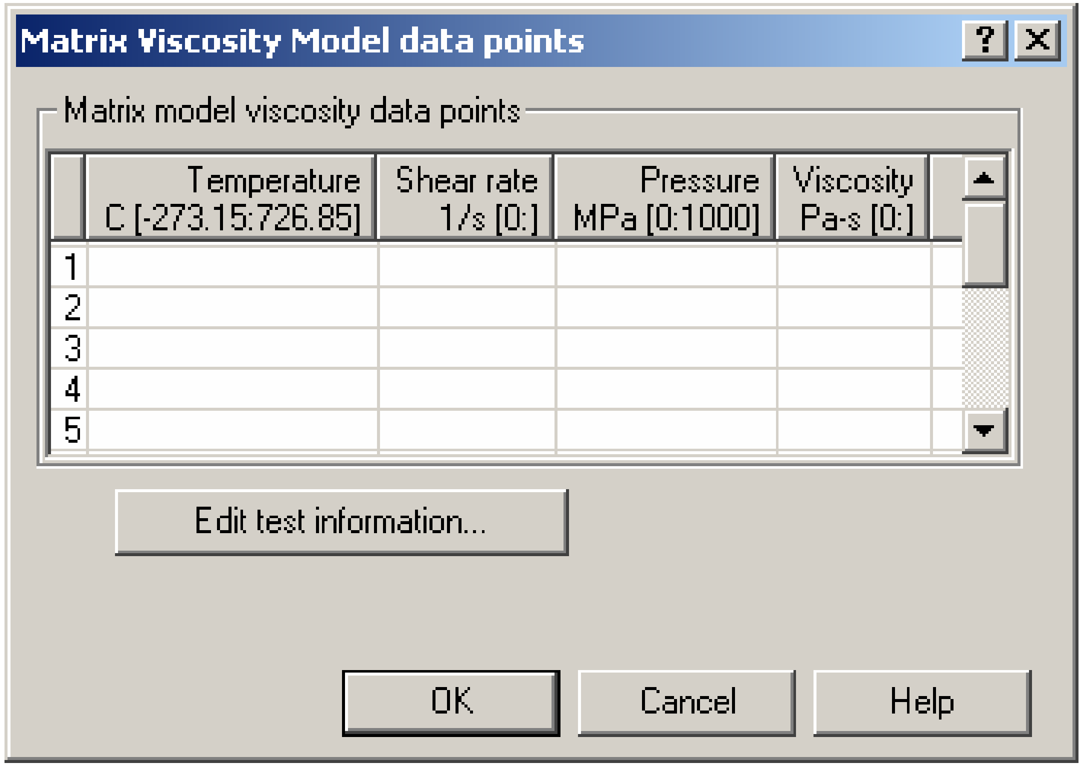
LCP – Complex temperature dependence



- Y.Fan, S.Dai and R.I. Tanner; Korea Australia Rheology Journal **15** (2003) 109

The Matrix Model

- Can capture unusual transitions that the Cross model cannot



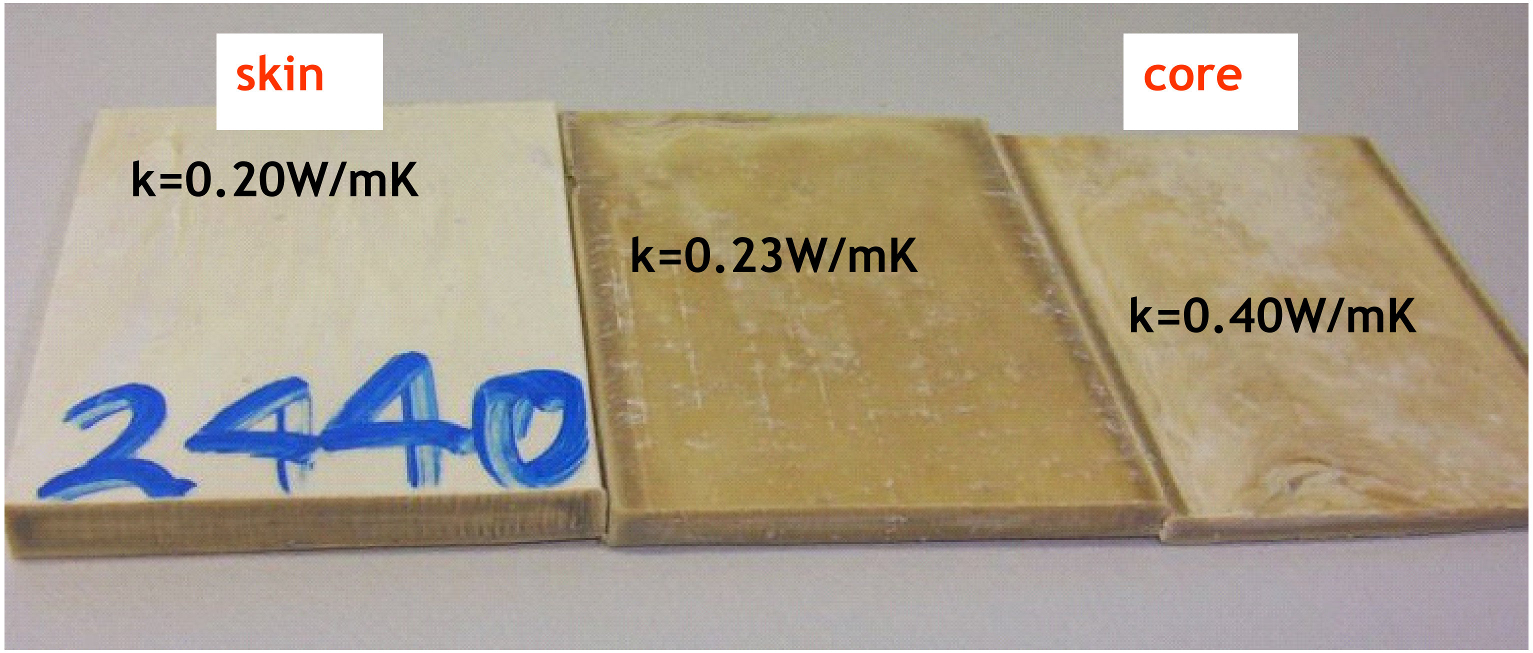
Matrix Viscosity Model data points

Matrix model viscosity data points

	Temperature C [-273.15:726.85]	Shear rate 1/s [0:]	Pressure MPa [0:1000]	Viscosity Pa-s [0:]
1				
2				
3				
4				
5				

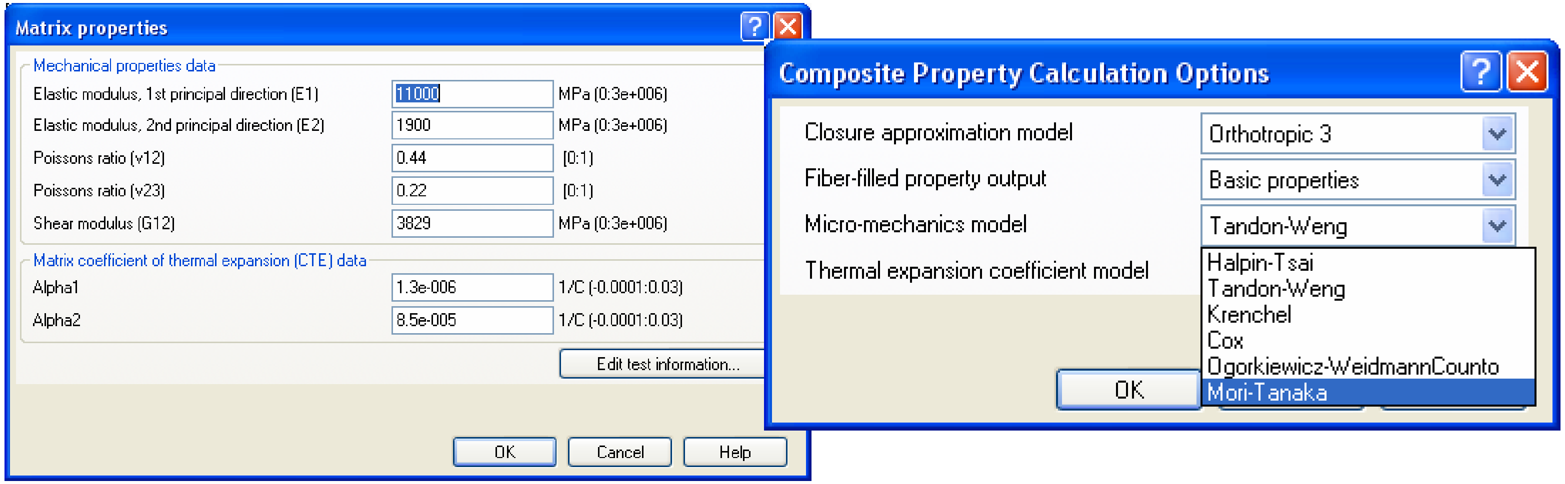
LCP - thermal conductivity and depth

- The variation in conductivity in the skin and core layers can be measured by milling to different depths



Improved Warpage Accuracy for Fiber filled LCP’s

- New Micromechanics model: Mori-Tanaka
  - Targeted to improve fiber filled LCP materials by allowing anisotropic mechanical properties for the LCP matrix to be used
  - Influence on warpage results using:
    - Isotropic matrix → identical to Tandon-Weng
    - Slightly anisotropic matrix → very minor advantage over Tando-Weng



Matrix properties

Mechanical properties data

Elastic modulus, 1st principal direction (E1)	11000	MPa (0:3e+006)
Elastic modulus, 2nd principal direction (E2)	1900	MPa (0:3e+006)
Poissons ratio (v12)	0.44	[0:1)
Poissons ratio (v23)	0.22	[0:1)
Shear modulus (G12)	3829	MPa (0:3e+006)

Matrix coefficient of thermal expansion (CTE) data

Alpha1	1.3e-006	1/C (-0.0001:0.03)
Alpha2	8.5e-005	1/C (-0.0001:0.03)

Composite Property Calculation Options

Closure approximation model: Orthotropic 3

Fiber-filled property output: Basic properties

Micro-mechanics model: Tandon-Weng

Thermal expansion coefficient model

Residual Stress Calculation

$$\sigma_{ij} = \int_0^t \overbrace{c_{ijkl}\left(\xi(t)-\xi(t')\right)}^{\textbf{Mechanical Properties}} \overbrace{\left(\frac{\partial \varepsilon_{kl}}{\partial t'} - \alpha_{kl}\frac{\partial T}{\partial t'}\right)}^{\textbf{Total Strain}} dt'$$

$$\sigma = E \times \varepsilon$$

Residual Stress Calculation

$$\sigma_{ij} = \int_0^t \overbrace{c_{ijkl}}^{\text{Mechanical properties}} \left(\xi(t) - \xi(t')\right) \left(\underbrace{\frac{\partial \varepsilon_{kl}}{\partial t'}}_{\text{Density, Pressure}} - \overbrace{\alpha_{kl}}^{\text{Thermal expansion coefficients}} \underbrace{\frac{\partial T}{\partial t'}}_{\text{Temperature}} \right) dt'$$

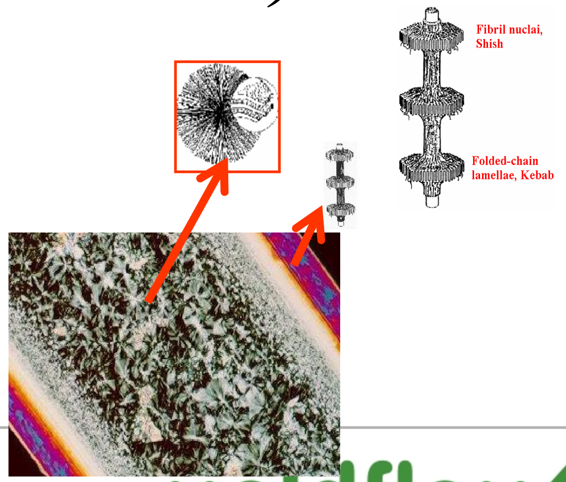
Residual Stress Calculation

Mechanical properties

Thermal expansion coefficients

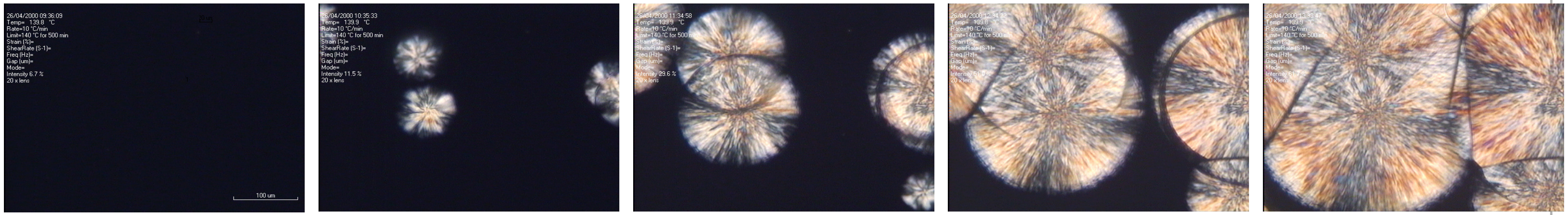
$$\sigma_{ij} = \int_0^t c_{ijkl}\left(\xi(t)-\xi(t')\right)\left(\frac{\partial \varepsilon_{kl}}{\partial t'} - \alpha_{kl}\frac{\partial T}{\partial t'}\right)dt'$$

- Depend on morphology



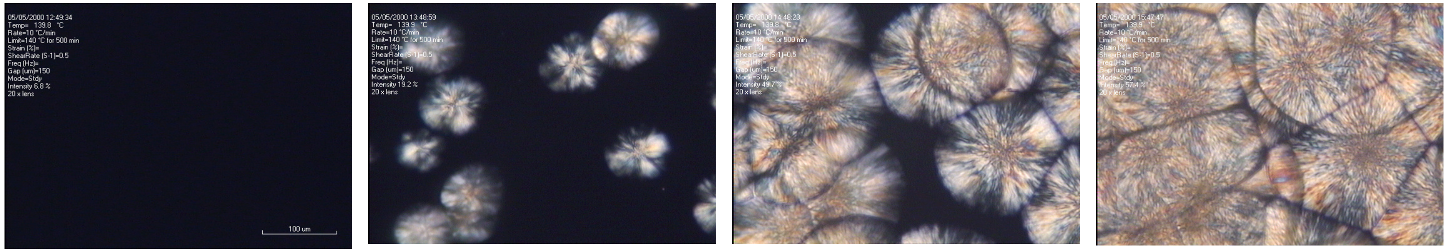
Crystallisation and Shear: Eltex PHV 252

Tc = 140°C / without shear :



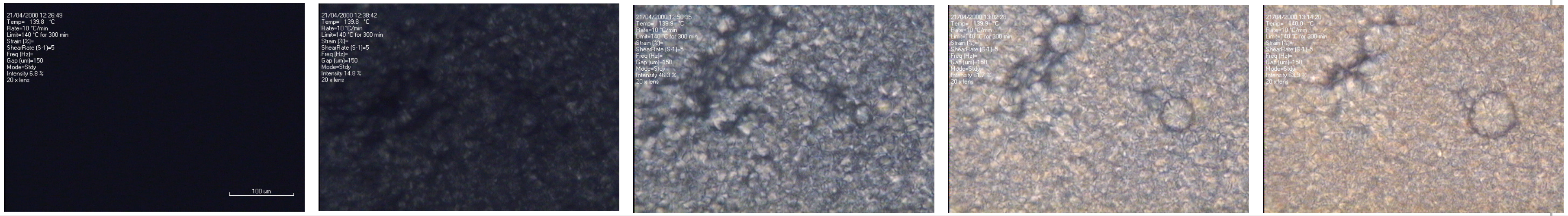
t = 0 | t = 60 min | t = 120 min | t = 180 min | t = 240 min

Tc = 140°C / $\gamma = 0.5\ s^{-1}$ / ts = 10s :



t = 0 | t = 60 min | t = 120 min | t = 180 min

Tc = 140°C / $\gamma = 5\ s^{-1}$ / ts = 10s :



t = 0 | t = 12 min | t = 24 min | t = 36 min | t = 48 min

Koscher & Fulchiron, Polymer 2002

Crystallisation

- Shear
  - Affects nucleation
  - Decreases crystallisation time

Eder, Janeschitz Kriegl, Lidauer, Prog. Polymer Sci. 1990

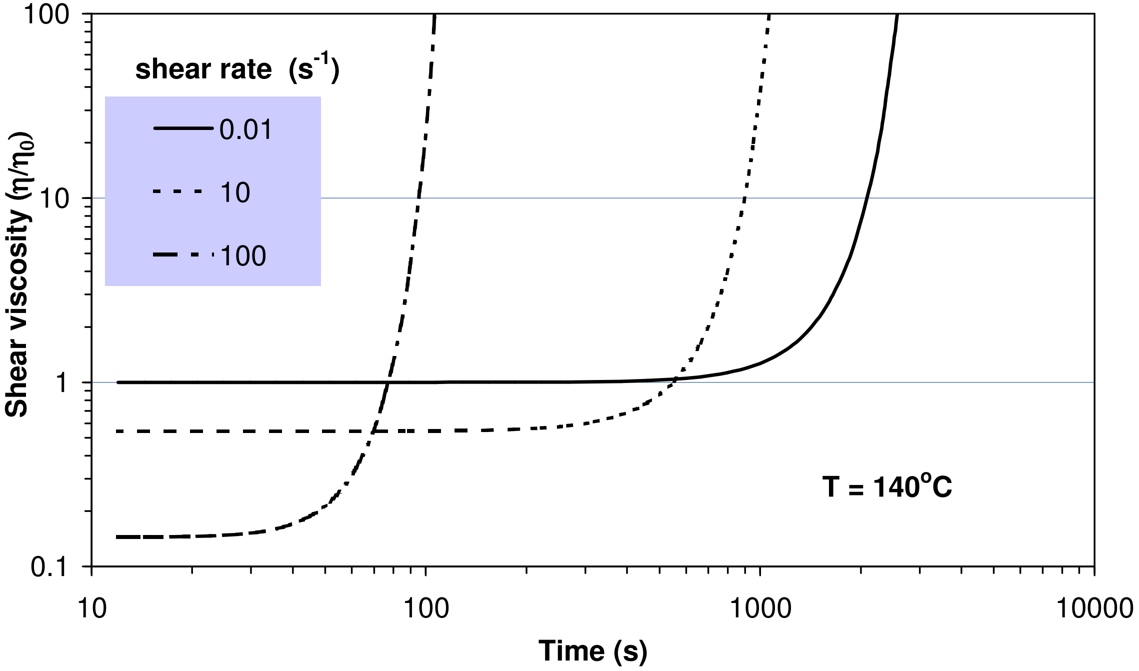
- High shear for short time more effective than low shear for longer time

Vleeshouwers and Meijer - Rheol. Acta. 1996

- Shearing for longer periods affects morphology
  - Crystallisation time unchanged
  - Formation of row nuclei

Kumaraswamy et. al. - Macromolecules 1999.
Acierno et. al. - Rheol. Acta. 2003.
Koscher and Fulchiron, Polymer, 2003.

Effect of FIC on Viscosity



$$\eta(\dot{\gamma},\alpha)=\eta_a\left(1+\frac{(\alpha/A)^{\beta_1}}{(1-\alpha/A)^{\beta}}\right),\ \alpha<\mathrm{A}$$

For rough particles A ~0.44 Tanner - JNNFM 2002

Crystallisation & Conductivity

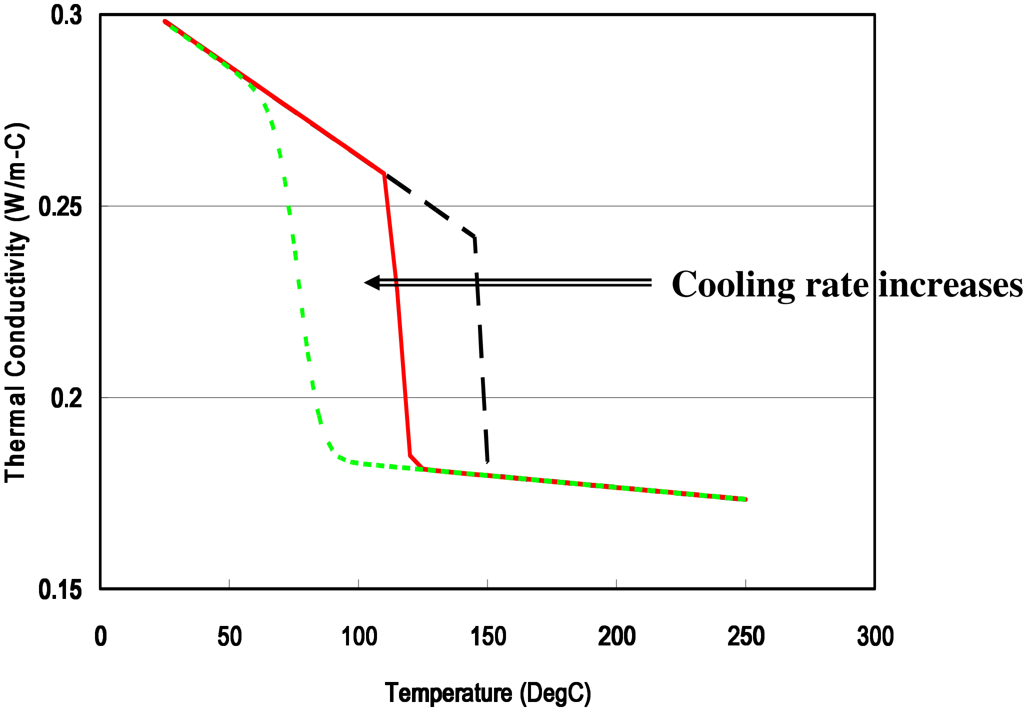
Slab model

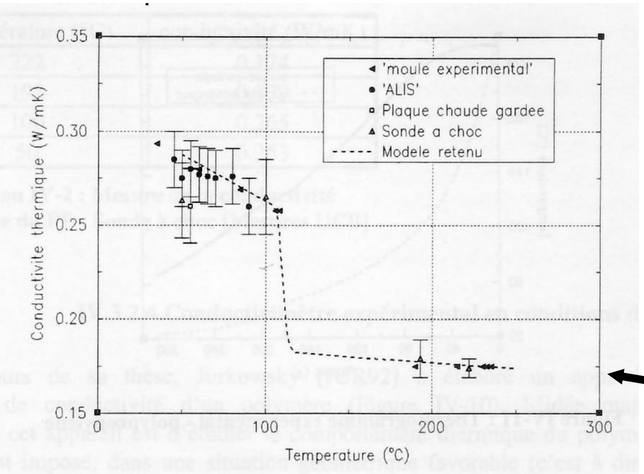
$$\mathbf{k}^{-1} = (1-\alpha)\mathbf{k}_a^{-1} + \alpha\mathbf{k}_s^{-1}$$

a: amorphous phase

s: solid (semi-crystalline) phase

α: *relative crystallinity*



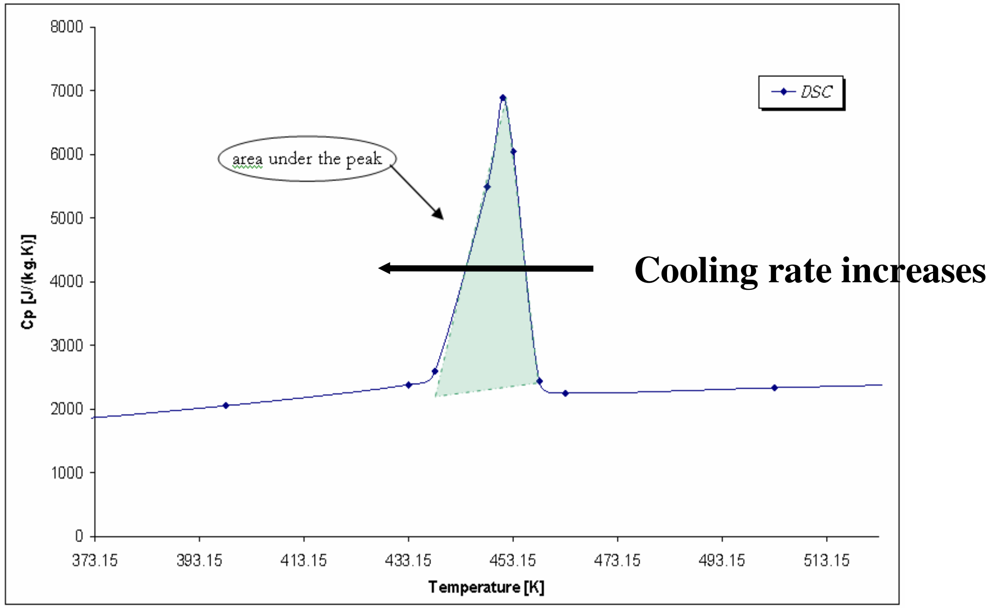


(Experimental data

P. Geraldine, PhD thesis, University of Nantes, 2002)

Specific Heat & Cystallisation

- Depends on Cooling Rate



- Link to crystallisation

$$c_p(\alpha,T)=\alpha c_{p_s}(T)+(1-\alpha)c_{p_a}(T)$$

Density & Crystallisation

- PVT measured under “static” conditions
- Modify with crystallisation
  - Flow induced
  - Temperature and rate of temperature change

$$v = \alpha v_s + (1 - \alpha) v_a$$

Crystallisation Model

- Kolmorgoroff

$$\alpha_f = C_m \int_0^t \dot{N}(s) \left[\int_s^t G(u)\,du \right]^m ds$$

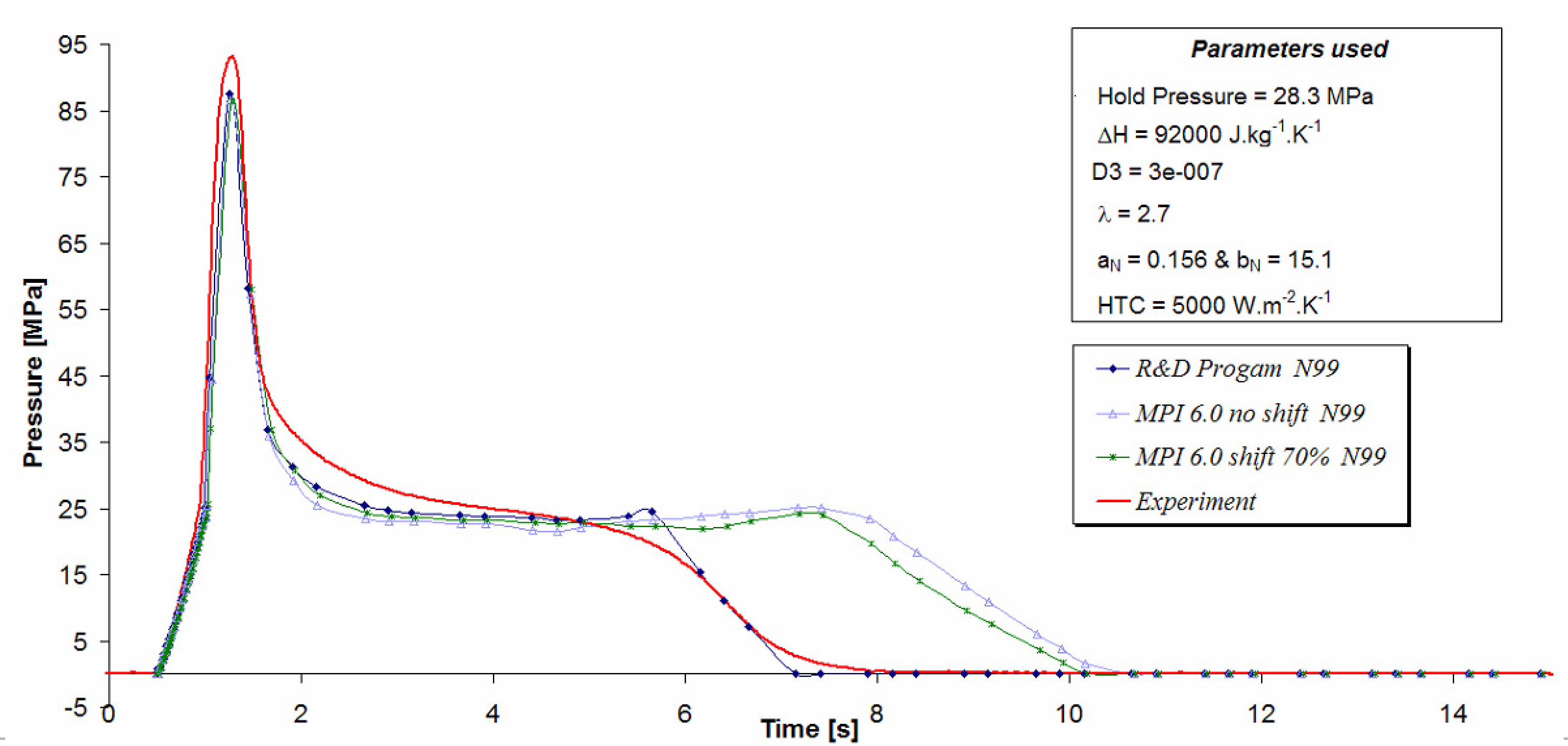
$$\alpha = 1 - exp(-\alpha_f)$$

- Accounts for affect of
  - Temperature
  - Rate of temperature change
  - Flow induced crystallisation

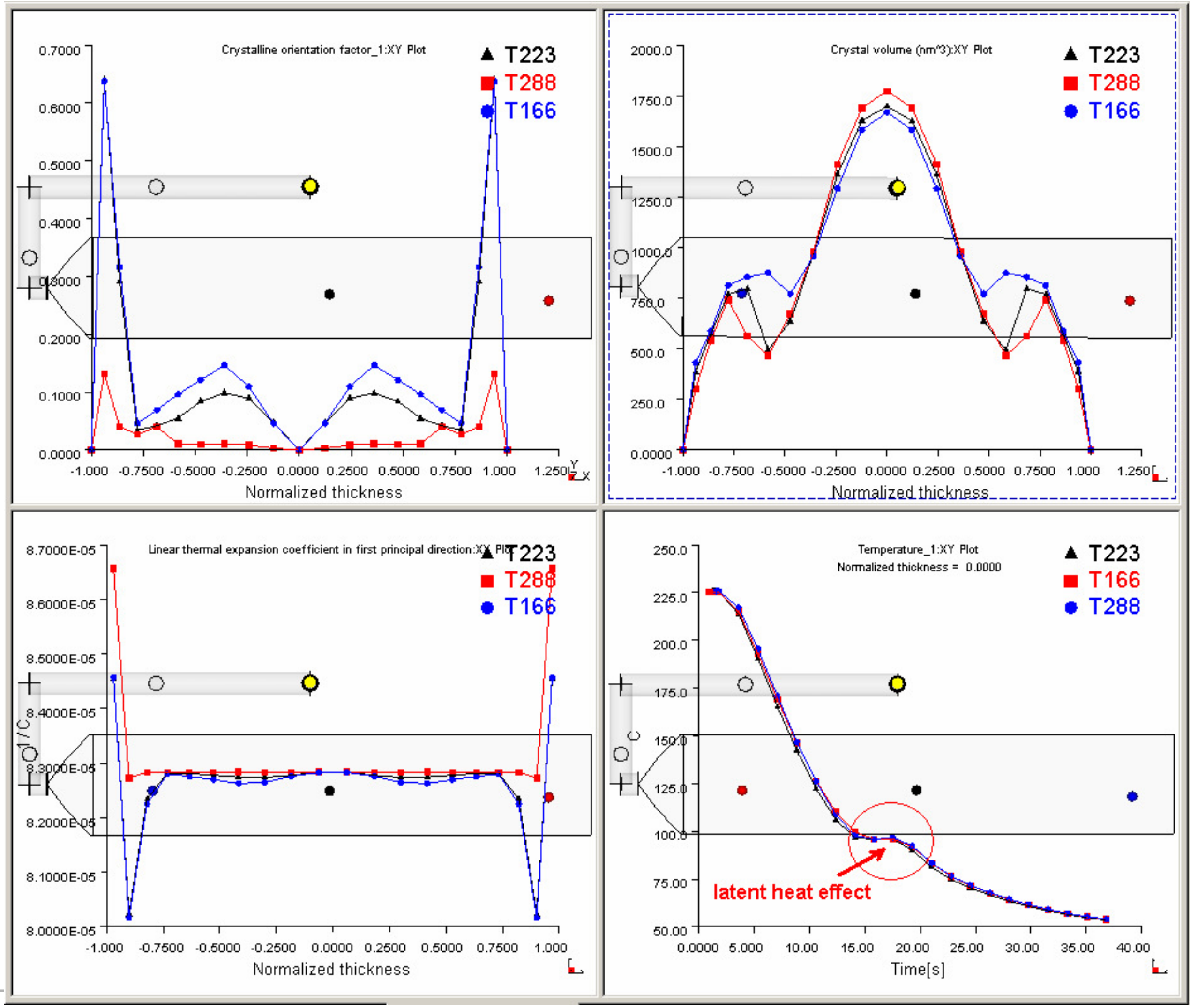
moldflow®
plastics made perfect™

Pressure Predictions

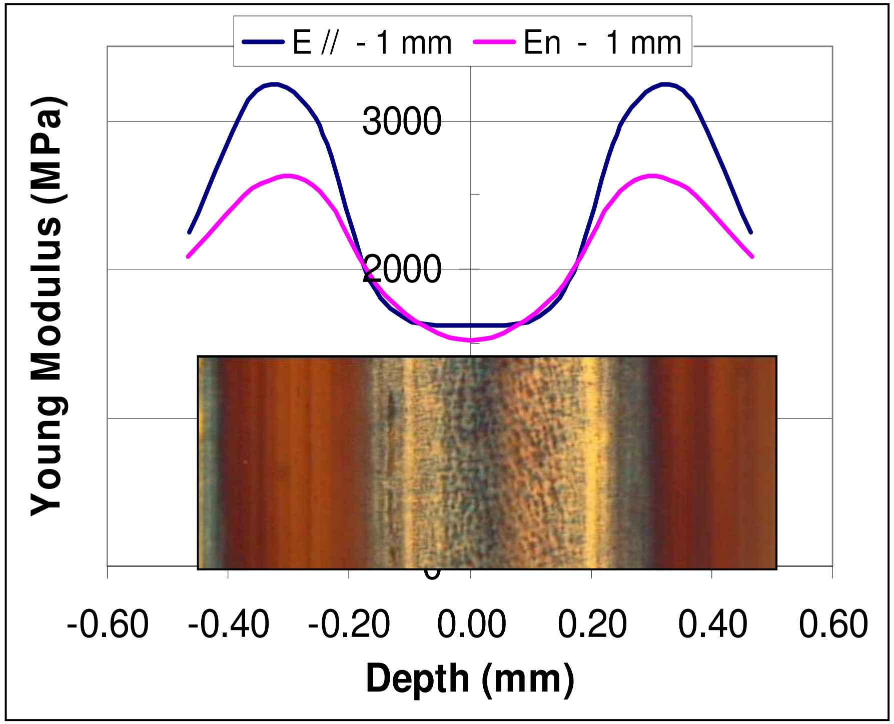
✓ PP (thickness=3.0mm)



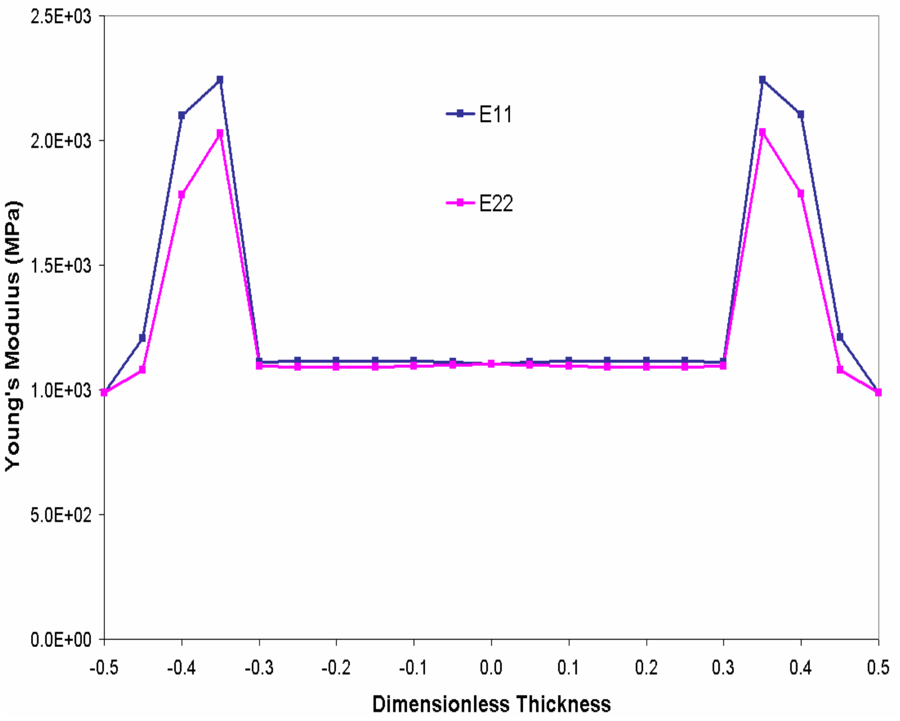
New Results


Crystalline orientation factor_1:XY Plot
▲ T223
■ T288
● T166
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
-1.000
-0.7500
-0.5000
-0.2500
0.0000
0.2500
0.5000
0.7500
1.000
1.250
Normalized thickness
Crystal volume (nm^3):XY Plot
▲ T223
■ T288
● T166
2000.0
1750.0
1500.0
1250.0
1000.0
750.0
500.0
250.0
0.0000
-1.000
-0.7500
-0.5000
-0.2500
0.0000
0.2500
0.5000
0.7500
1.000
1.250
Normalized thickness
Linear thermal expansion coefficient in first principal direction:XY Plot
▲ T223
■ T288
● T166
8.7000E-05
8.6000E-05
8.5000E-05
8.4000E-05
8.3000E-05
8.2000E-05
8.1000E-05
8.0000E-05
1 / C
-1.000
-0.7500
-0.5000
-0.2500
0.0000
0.2500
0.5000
0.7500
1.000
Normalized thickness
Temperature_1:XY Plot
Normalized thickness = 0.0000
▲ T223
■ T166
● T288
250.0
225.0
200.0
175.0
150.0
125.0
100.0
75.00
50.00
C
0.0000
5.000
10.00
15.00
20.00
25.00
30.00
35.00
40.00
Time[s]
latent heat effect

Young’s Modulus (1mm part)

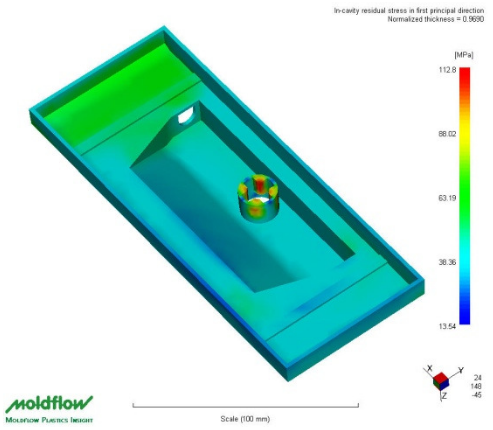


Experiments

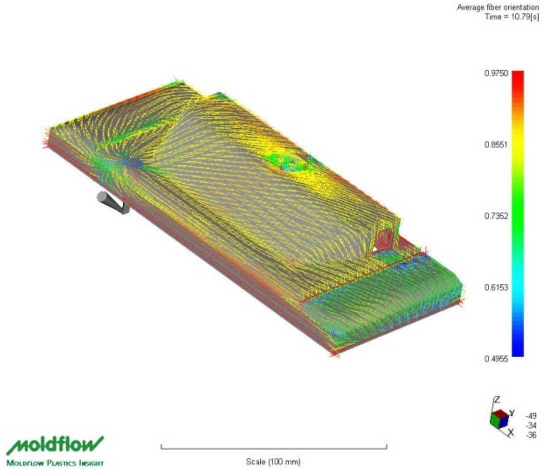


Prediction

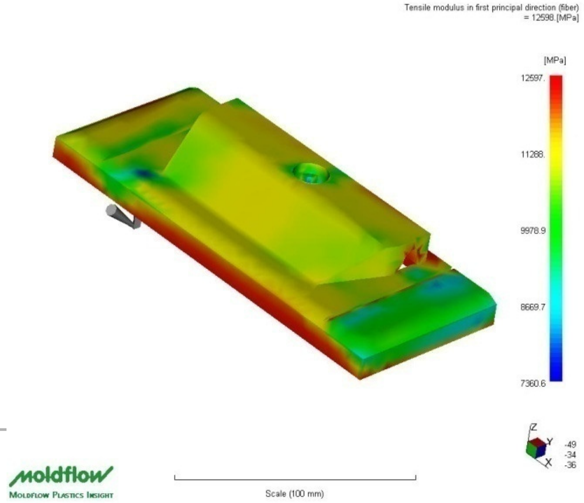
Stresses, Orientation & Modulus



In-cavity Stresses



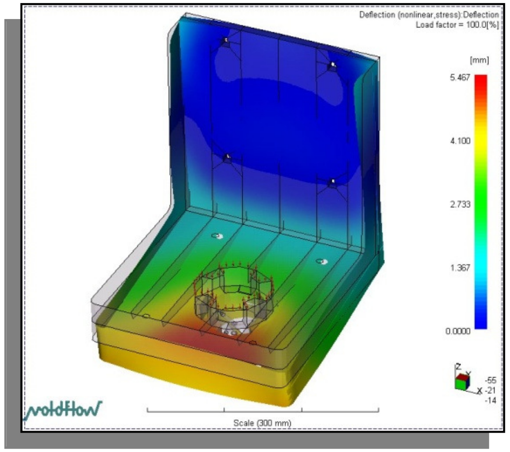
Fibre Orientation



Modulus

Structural Analysis (FEA)

- Interface to:
  - Abaqus
  - Ansys
  - Patran
  - Nastran
  - LS-Dyna



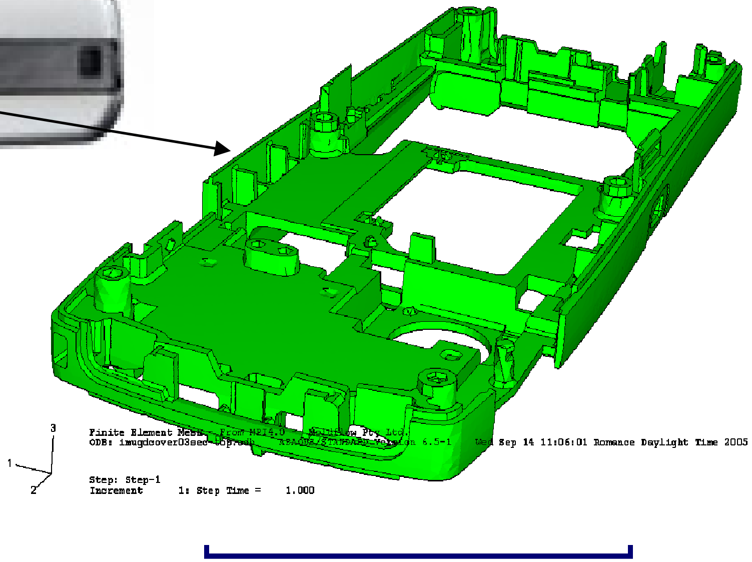
Exclusive structural analysis for optimising the structural integrity of plastic injection moulded parts.

Information Exported from Moldflow to FEA

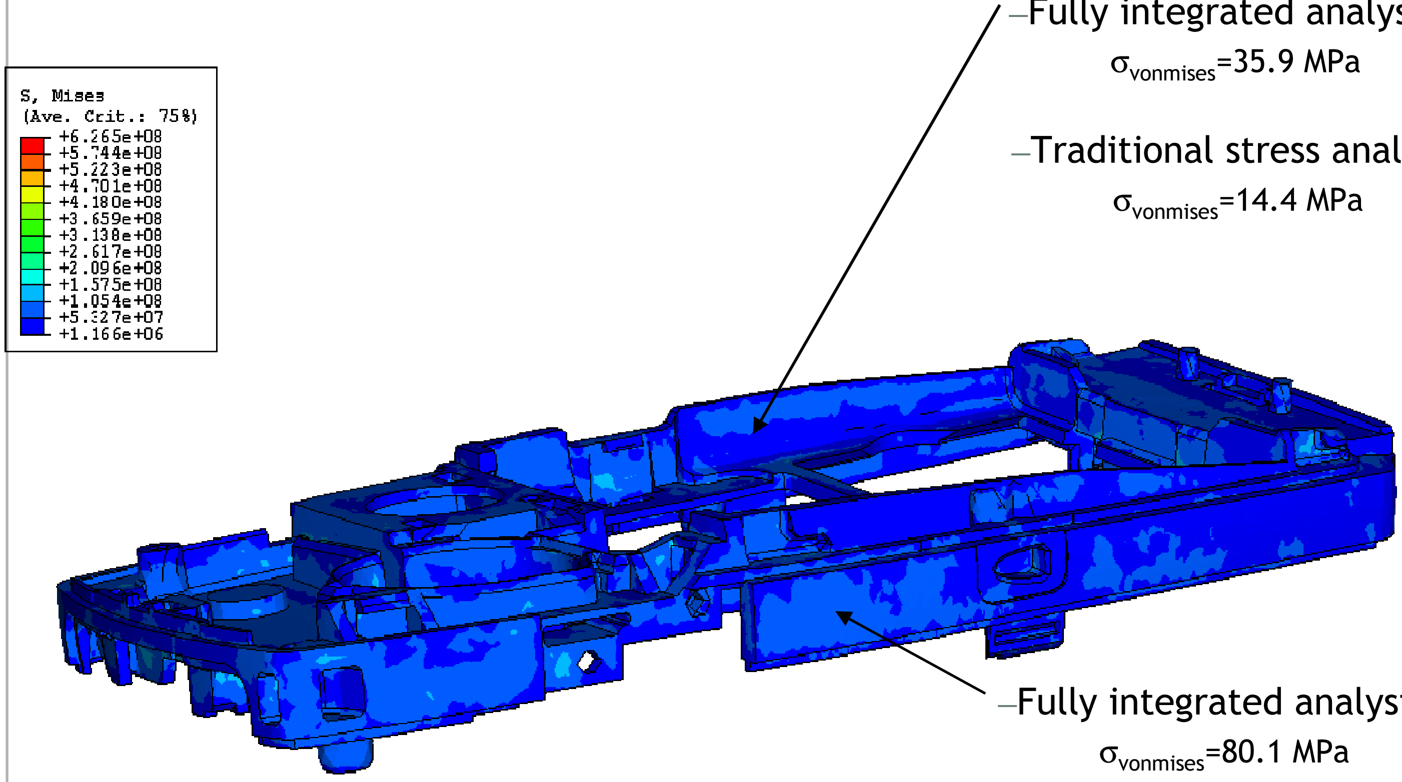
- Unfilled Materials
  - Elastic modulus, Shear modulus & Poisson’s ratio from Material database
  - Coefficient of thermal expansion (CTE) from Material database
  - Layer-wise (20 layers through the thickness of each element) Residual stresses
- Fiber-filled Materials
  - Layer-wise Elastic modulus, Shear modulus & Poisson’s ratio
  - Layer-wise CTE
  - Layer-wise Residual stresses
  - Layer-wise Fiber orientation angle

Example

Case Nokia 6230
Primary stiffening cover, essential for the entire phone stiffness



Stress Comparison



- Fully integrated analysis:

  $\sigma_{vonmises}$=35.9 MPa

- Traditional stress analysis:

  $\sigma_{vonmises}$=14.4 MPa

- Fully integrated analysis:

  $\sigma_{vonmises}$=80.1 MPa

- Traditional stress analysis:

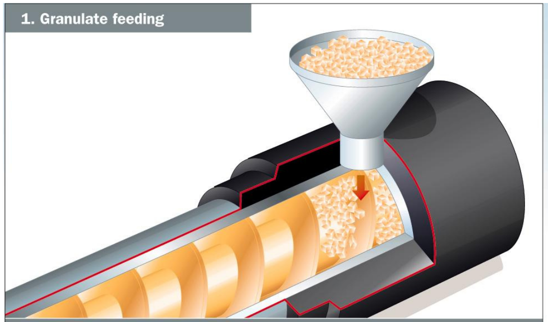
  $\sigma_{vonmises}$=17.2 MPa

Microcellular (MuCell®) Injection Moulding Simulation

- MuCell is a variation of foam molding
- This process is marketed by Trexel Inc.
- In this process a Super Critical Fluid (SCF) of Nitrogen (N_2) or Carbon Dioxide (CO_2) is mixed with polymer melt to create a single phase solution which is then injected into the cavity

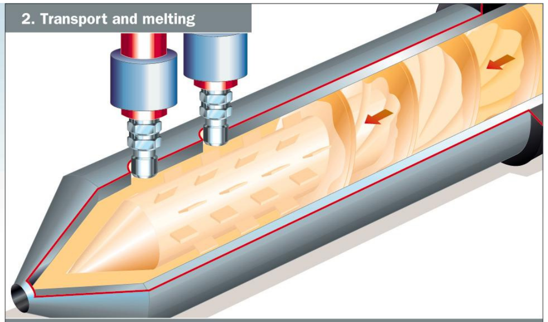
The MuCell Process

1. Creation of a single phase solution
2. Homogeneous Nucleation
3. Cell Growth
4. Part Formation



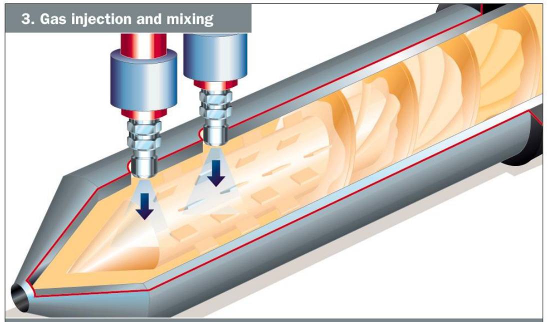
1. Granulate feeding

The rotating screw draws in the granulate from the material hopper and transports it in the direction of the screw tip.



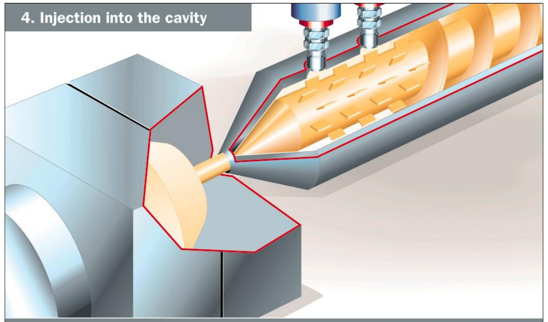
2. Transport and melting

The plastic is plastified and homogenised by heating while being transported.



3. Gas injection and mixing

The Gas is injected into the polymer melt and mixed.



4. Injection into the cavity

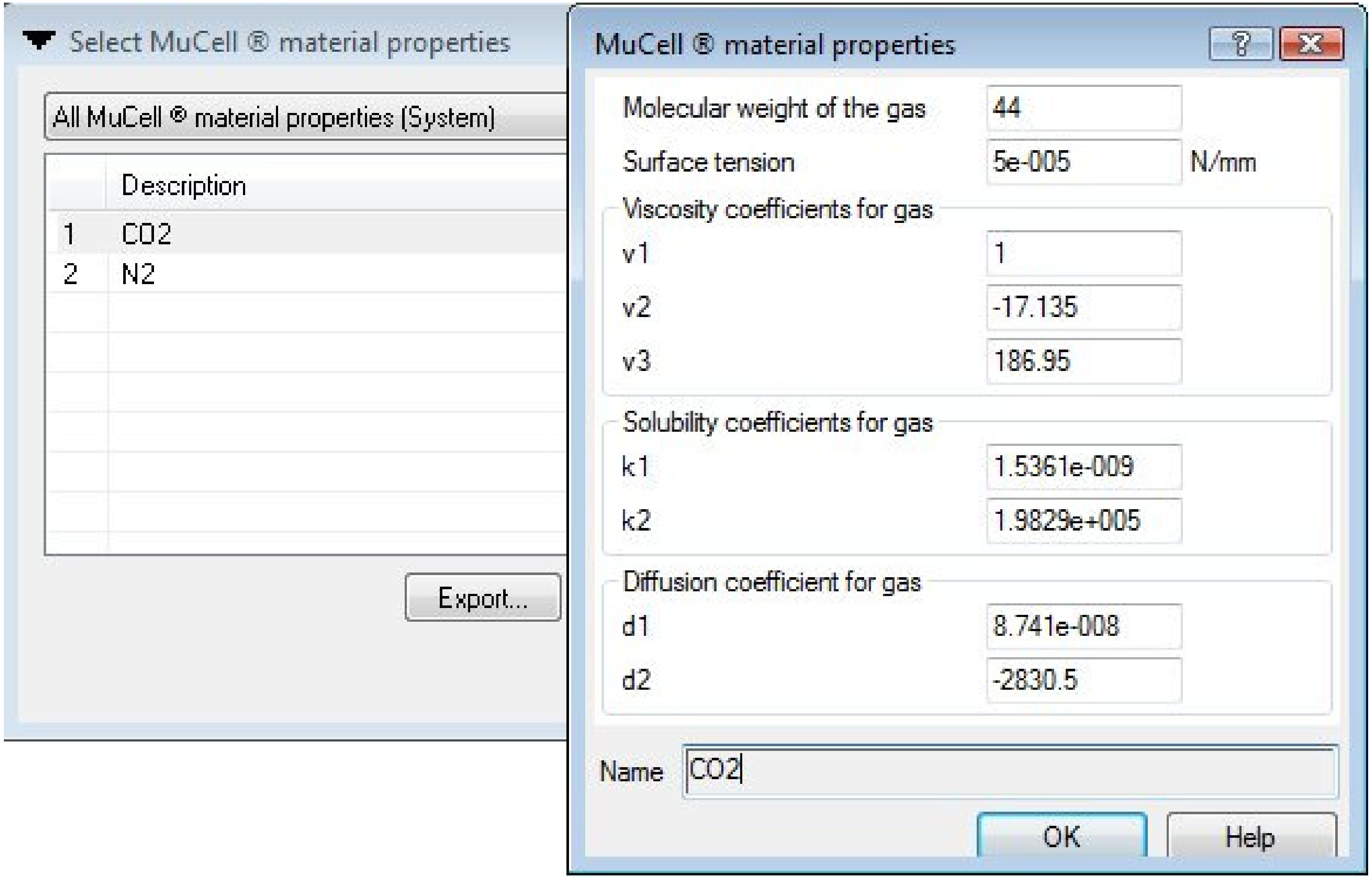
The plastics-gas mixture is under pressure and is injected into the injection moulding tool, where it forms small, finely distributed gas bubbles.

Image courtesy of Trexel Inc.

Advantages of MuCell

- Lighter parts (due to material reduction)
- Thin and difficult-to-fill sections can now be filled (due to reduction in material viscosity)
- Reduced cycle times
- Reduced pressures
- Reduced clamp tonnage
- Reduced part warpage

MuCell Gas Properties



Select MuCell ® material properties

All MuCell ® material properties (System)

	Description
1	CO2
2	N2

MuCell ® material properties

Molecular weight of the gas: 44

Surface tension: 5e-005 N/mm

Viscosity coefficients for gas

v1: 1

v2: -17.135

v3: 186.95

Solubility coefficients for gas

k1: 1.5361e-009

k2: 1.9829e+005

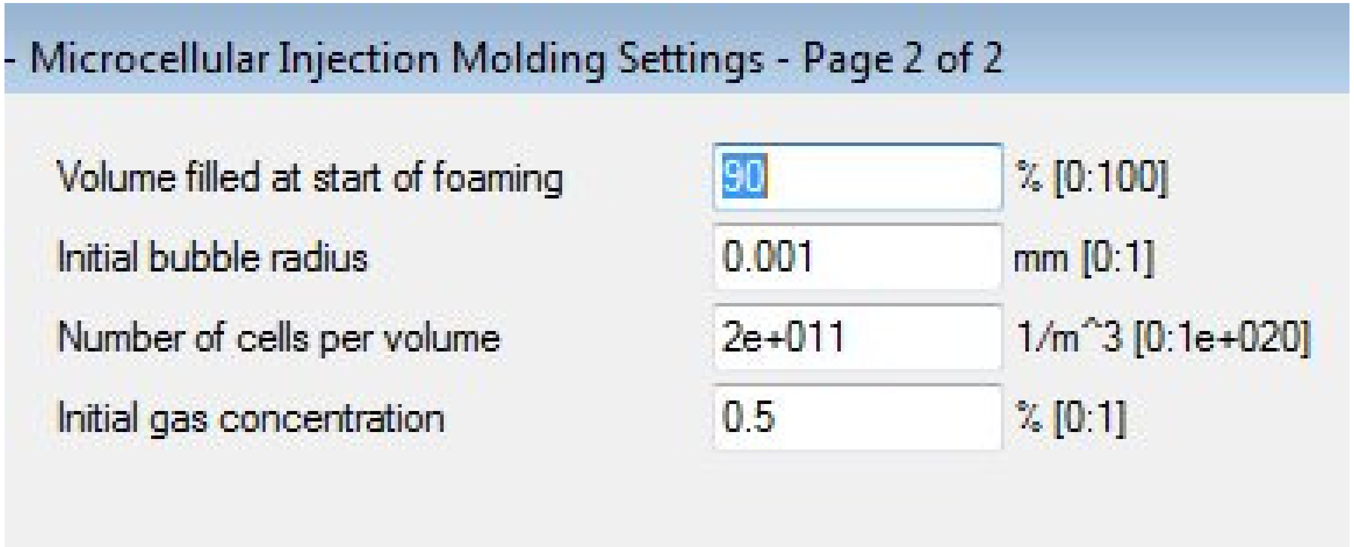
Diffusion coefficient for gas

d1: 8.741e-008

d2: -2830.5

Name: CO2

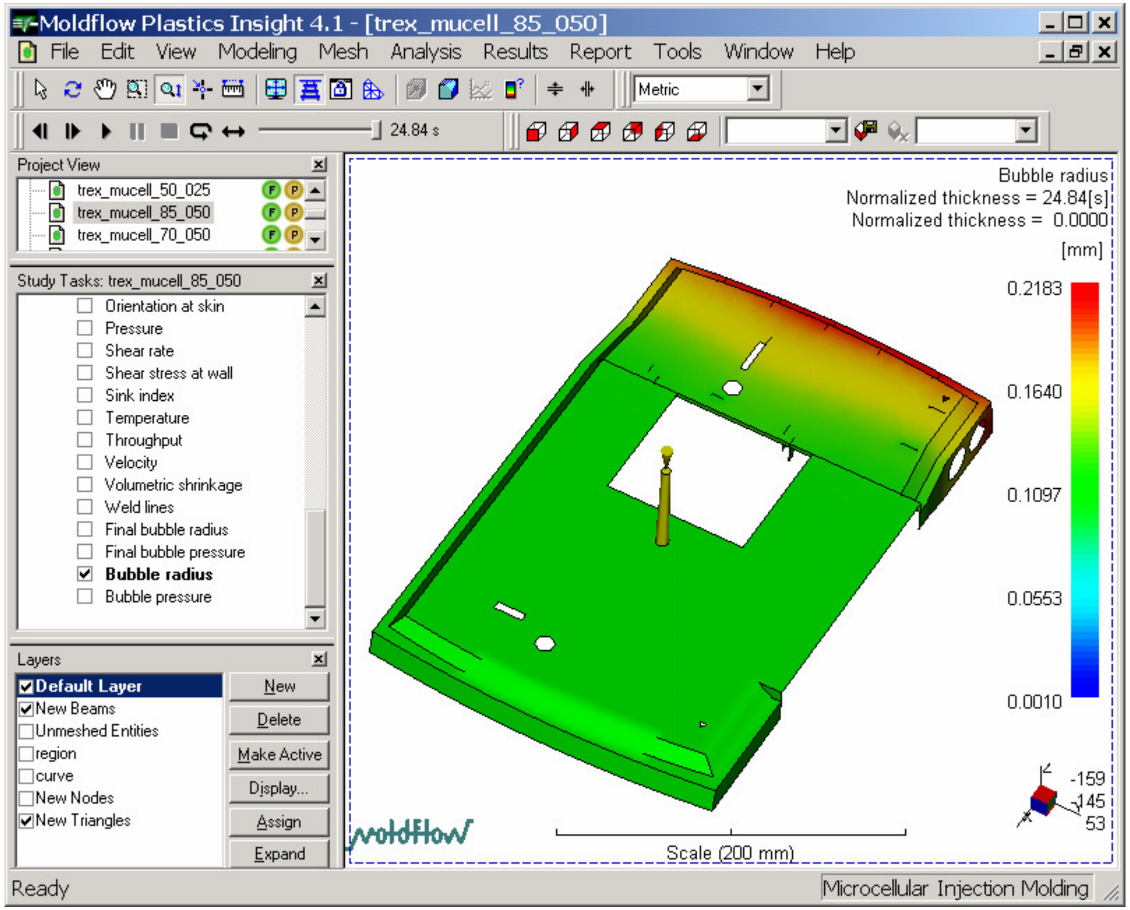
MuCell User Inputs



- Microcellular Injection Molding Settings - Page 2 of 2

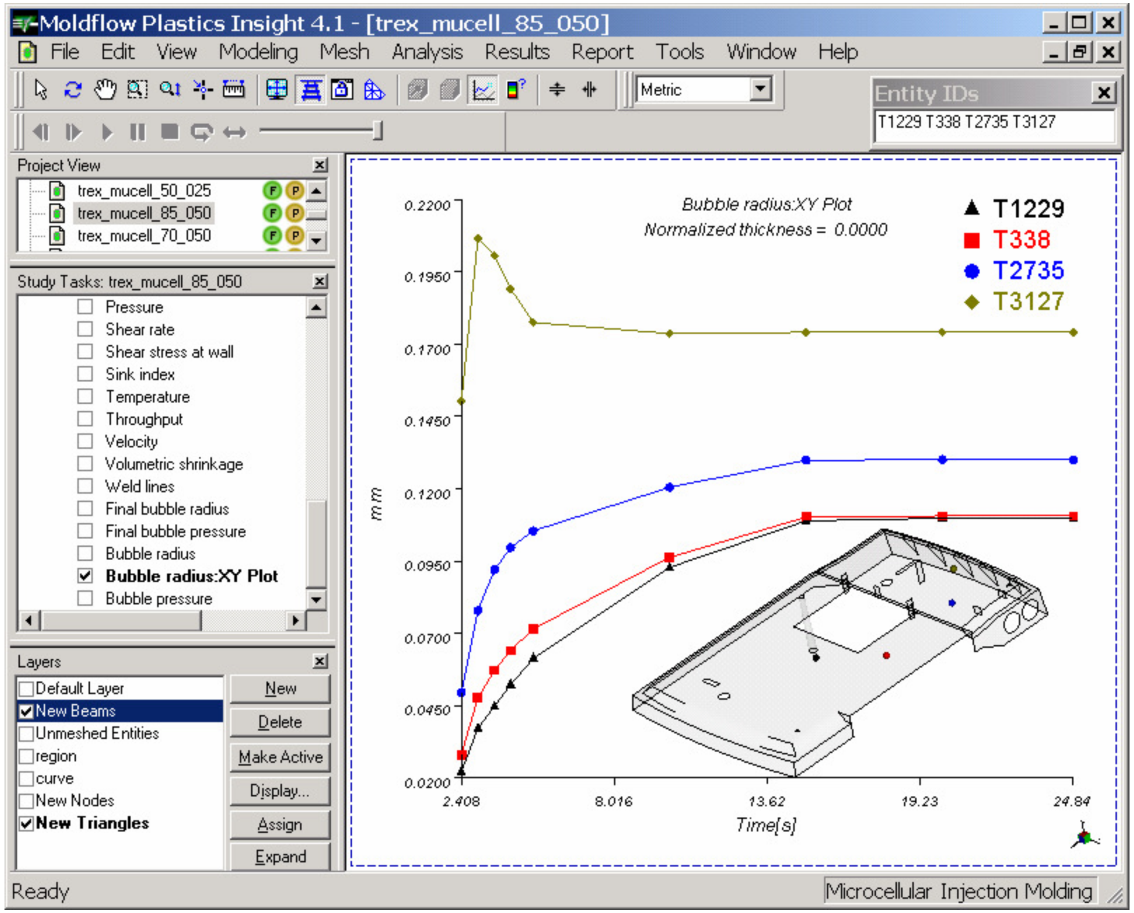
Volume filled at start of foaming	90	% [0:100]
Initial bubble radius	0.001	mm [0:1]
Number of cells per volume	2e+011	1/m^3 [0:1e+020]
Initial gas concentration	0.5	% [0:1]

Simulation Results



Bubble Radius at the end of cycle

Simulation Results



Entity IDs: T1229 T338 T2735 T3127

Study Tasks: trex_mucell_85_050

- ☐ Pressure
- ☐ Shear rate
- ☐ Shear stress at wall
- ☐ Sink index
- ☐ Temperature
- ☐ Throughput
- ☐ Velocity
- ☐ Volumetric shrinkage
- ☐ Weld lines
- ☐ Final bubble radius
- ☐ Final bubble pressure
- ☐ Bubble radius
- ☑ **Bubble radius:XY Plot**
- ☐ Bubble pressure

Layers

- ☐ Default Layer
- ☑ New Beams
- ☐ Unmeshed Entities
- ☐ region
- ☐ curve
- ☐ New Nodes
- ☑ **New Triangles**

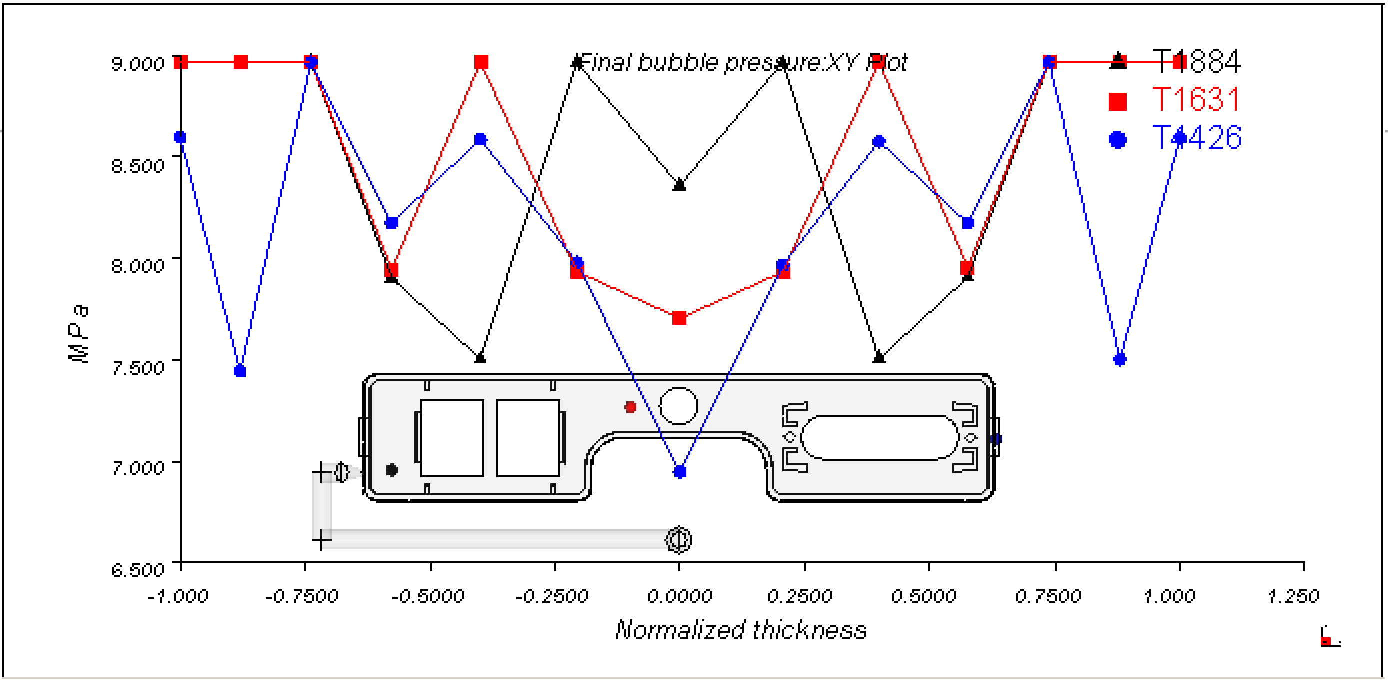
Ready | Microcellular Injection Molding

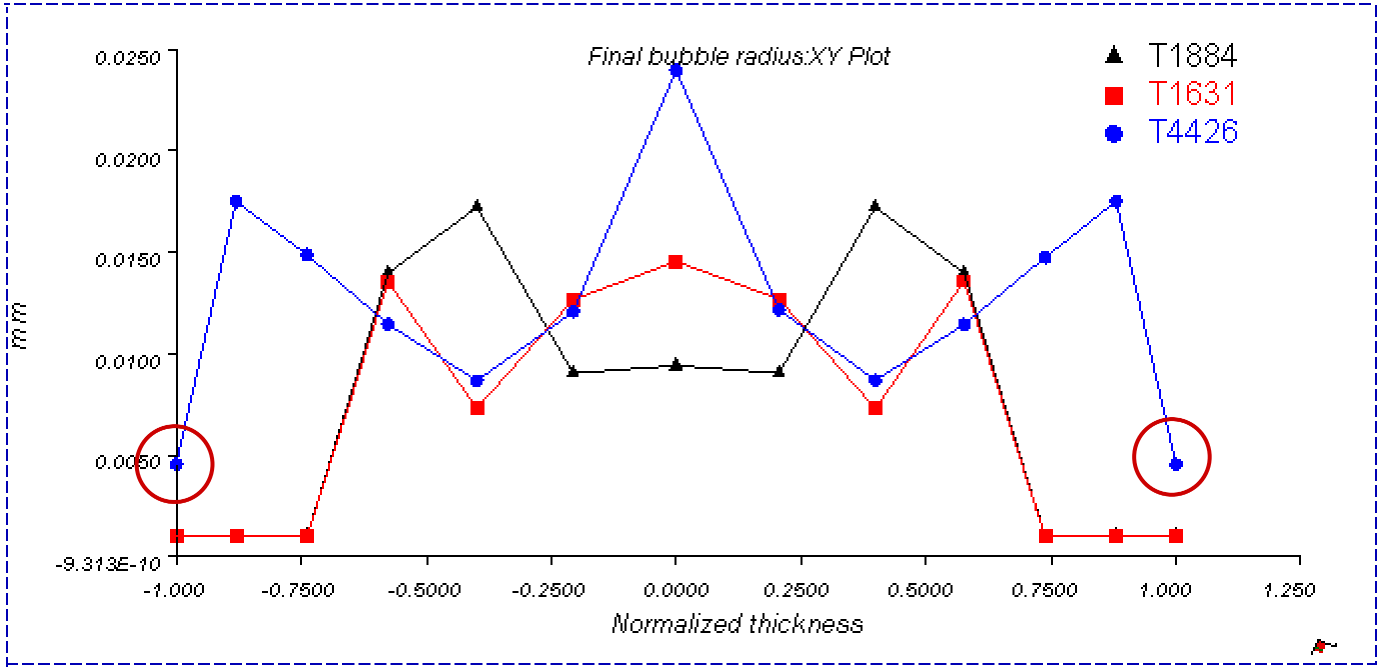
Bubble Radius as a function of time

Bubbles

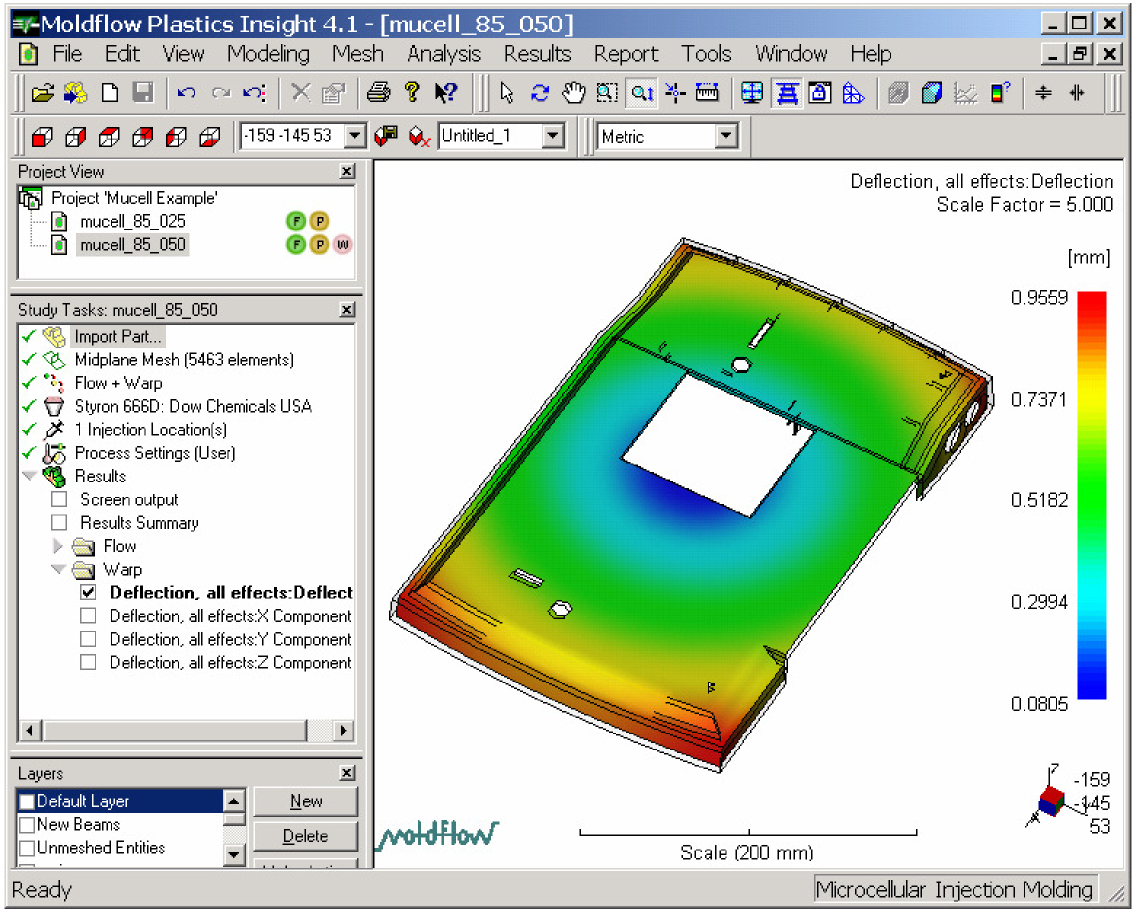
Three points to be compared:
black: near the gate
red: middle of the part
blue: end of flow

The blue one has a lower pressure and a bigger bubble radius at the wall than the other points.





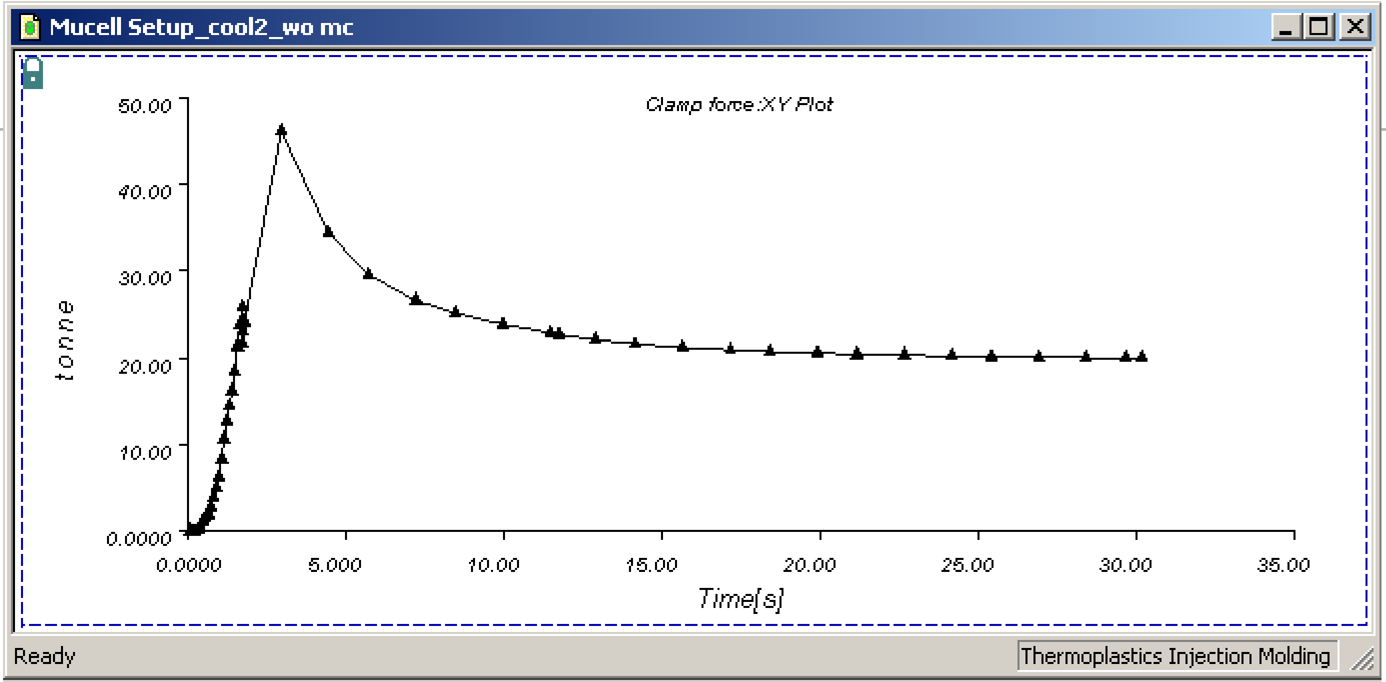
Simulation Results

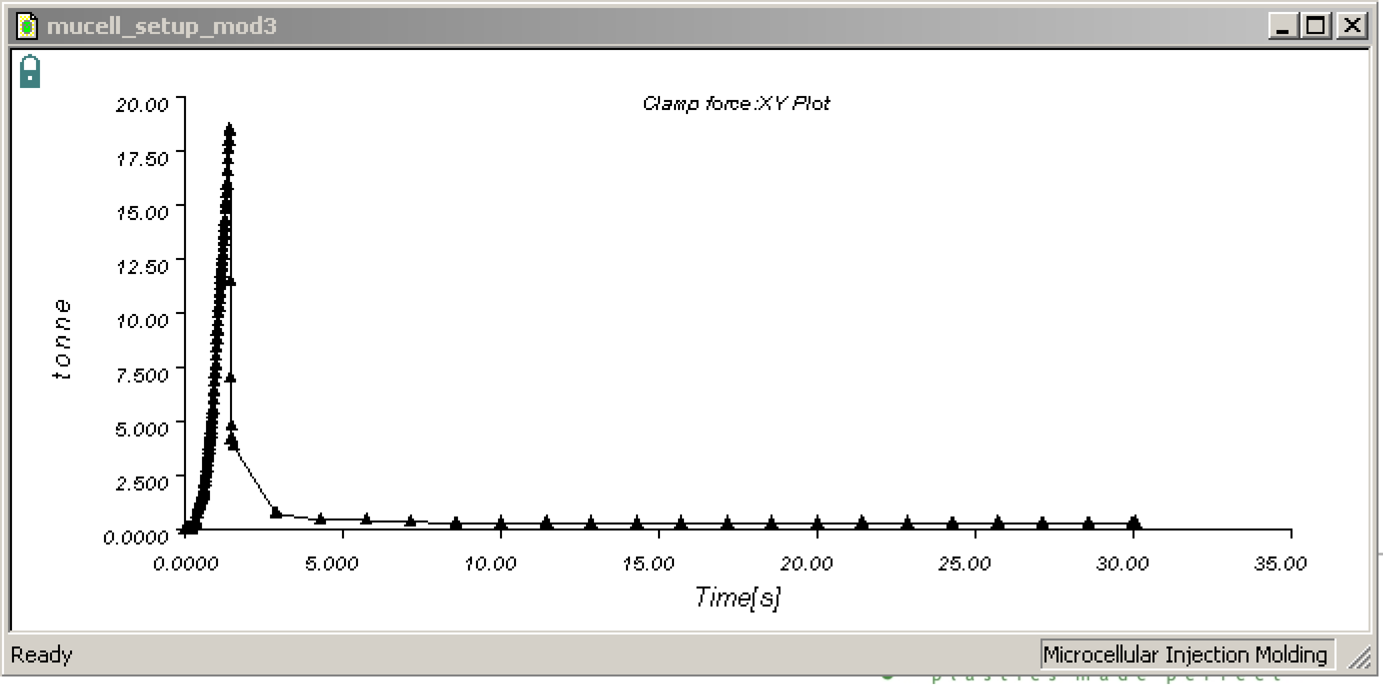


Predicted Shape & Magnitude of part deflection

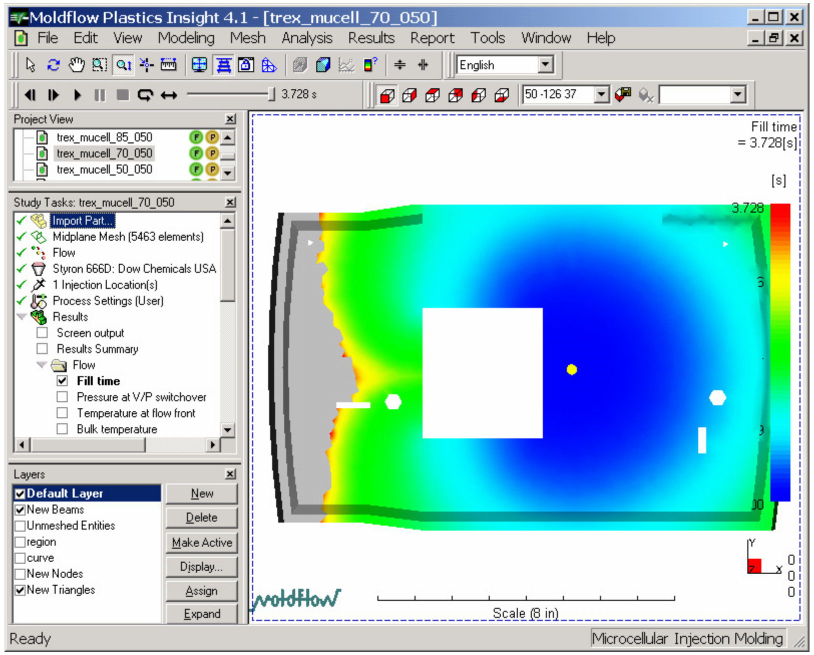
Clamp force

Lower clamp force with MuCell



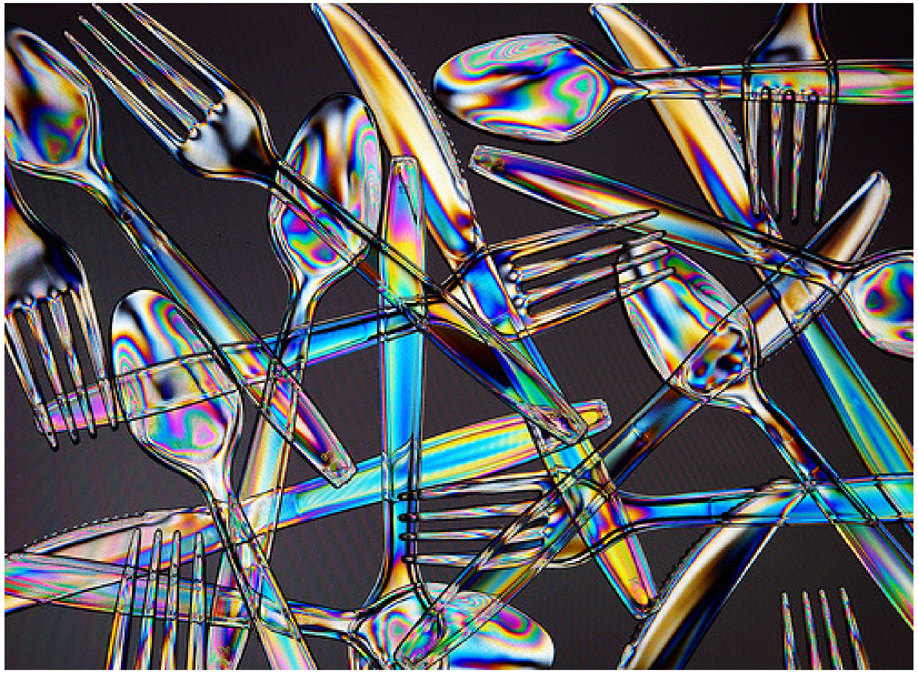


MuCell Validation



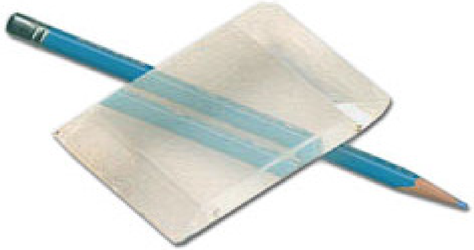
Short shot comparison for gas concentration of 0.5% (by weight) and shot size of 70%

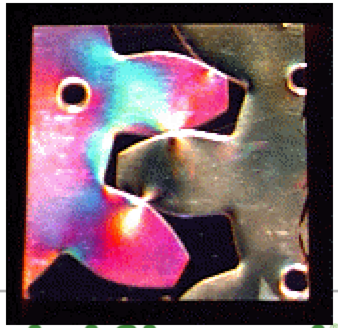
Birefringence



What is Birefringence?

- Definition: Birefringence is the change in the refractive index of polarised light passing through an object
- Birefringence may lead to crucial part defects
  - Blurred images
  - Double images
  - Poor optical performance





Birefringence: Polymers

- Birefringence can be caused by stresses in polymer
  - Flow induced stresses
  - Post warpage induced stresses
- Elastic deformation caused by residual stresses
- Viscoelastic deformation caused by flow orientation of polymer
- Will not be uniform in all regions of the part or through the thickness
- Need viscoelastic material data to predict change in optical properties

Birefringence Caused by Elastic Deformations

- Stress-optical law

$$\Delta n_{ii} = C_1 \sigma_{ii} + C_2 (\sigma_{11} + \sigma_{22} + \sigma_{33})$$

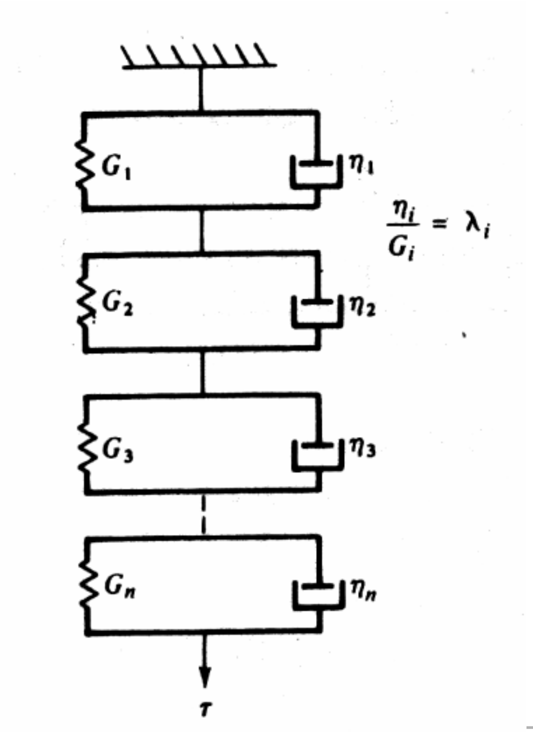
$$\Delta n_{ij} = C_1 \sigma_{ij} \qquad i \neq j$$

Δn_{ii}	Change in refractive index
σ	Stress
C_1	Stress-optical coefficient (anisotropic)
C_2	Stress-optical coefficient (isotropic)

The final residual stresses are determined after ejection.

Generalized Voigt-Kelvin Model

- Complex viscoelastic behaviour can be described by elements with different properties, coupled in series



$$\gamma_i(t) = \tau_o J_i (1 - e^{-t/\lambda_i})$$

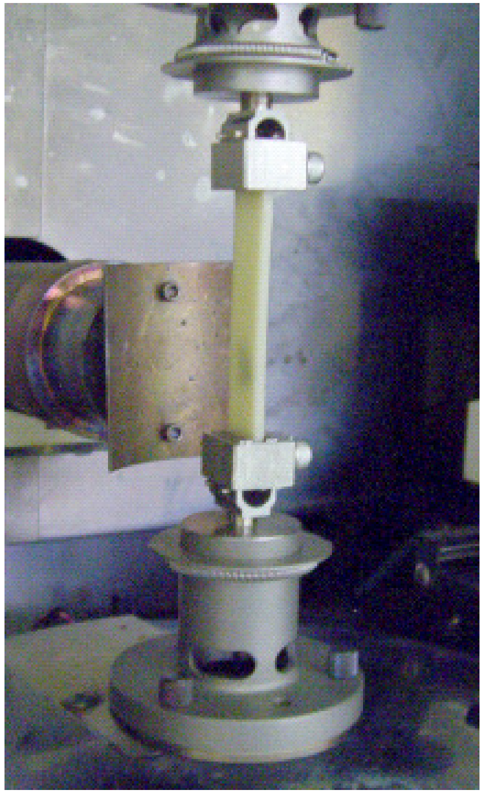
$$\gamma(t) = \tau_o \sum_{i=1}^{n} J_i (1 - e^{-t/\lambda_i})$$

$$J(t) = \frac{\gamma(t)}{\tau_o} = \sum_{i=1}^{n} J_i (1 - e^{-t/\lambda_i})$$

Testing Viscoelasticity - Methods

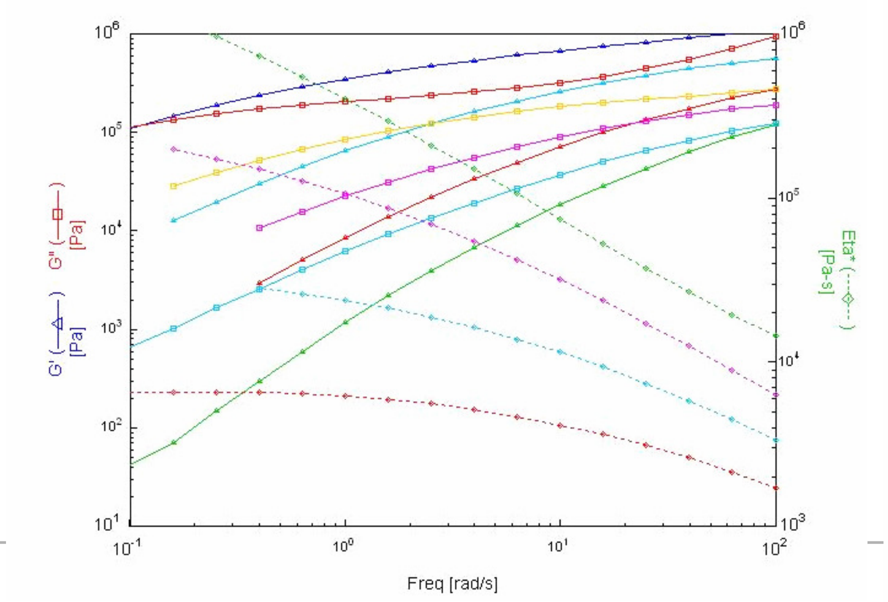
- Dynamic Mechanical Analysis
  - Parallel Plate

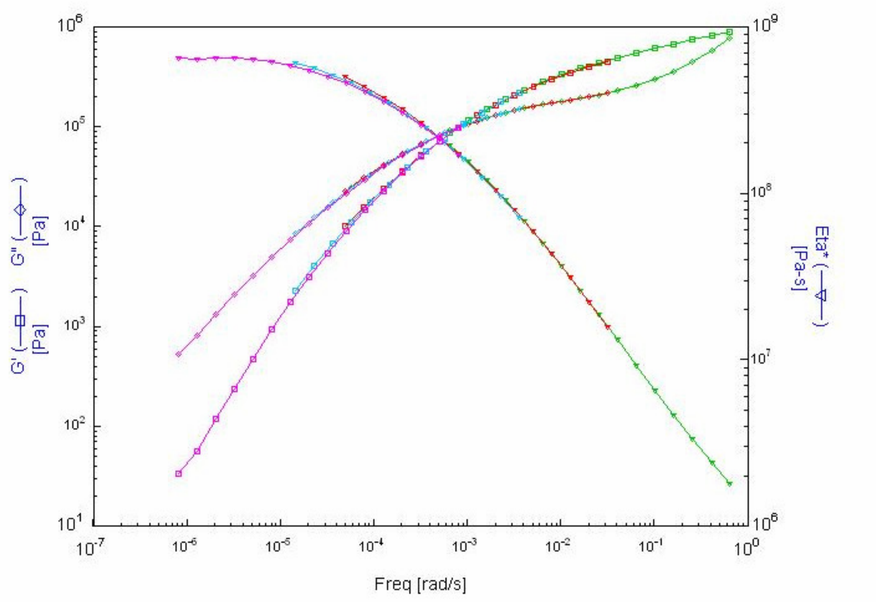
Rectangular Torsion



Viscoelastic data - Parallel Plate

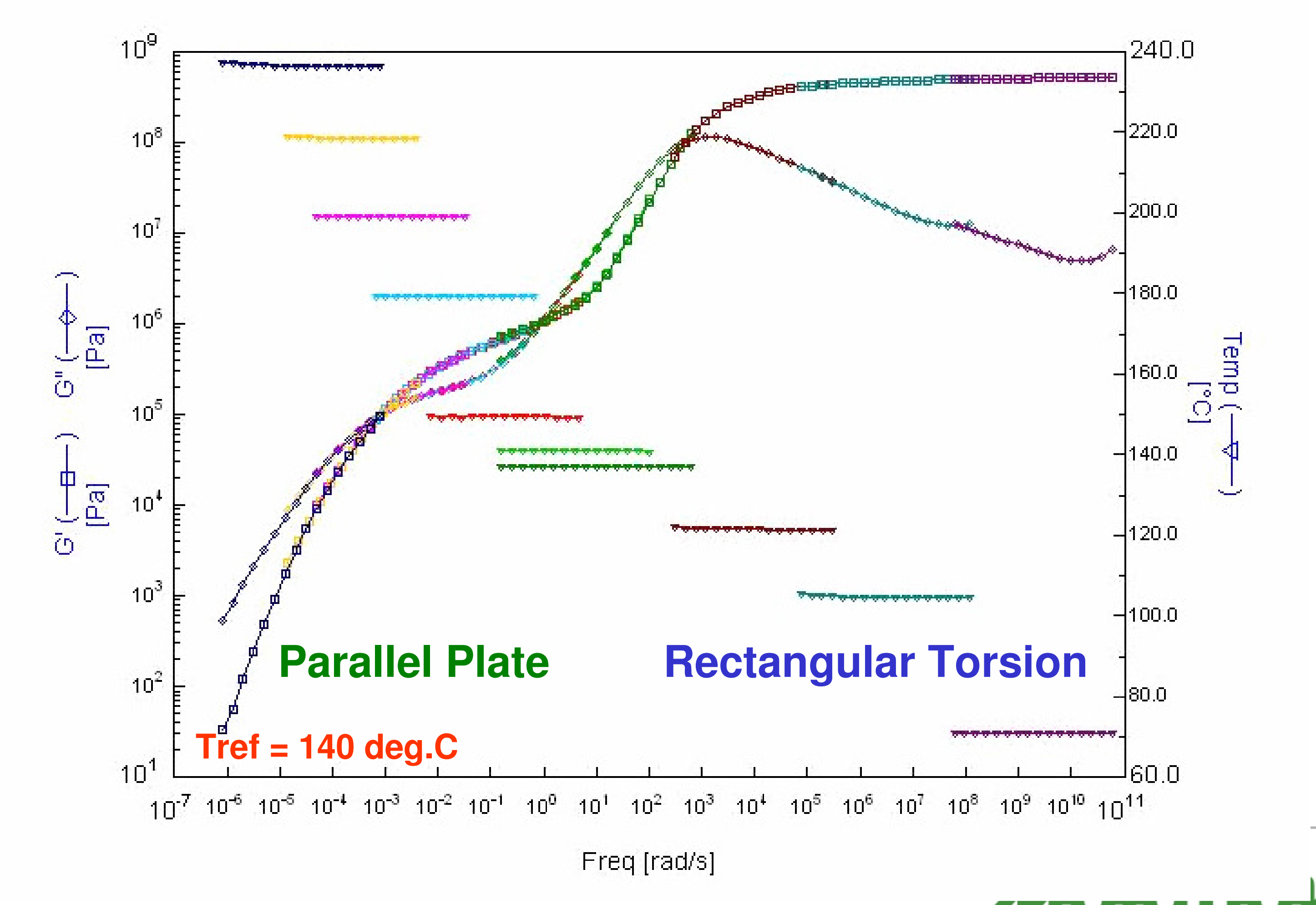
- The elastic modulus (G’), viscous modulus (G”) and Viscosity (eta) can be shifted to form a master curve using the principle of “time-temperature superposition”





Viscoelastic data – Master Curve

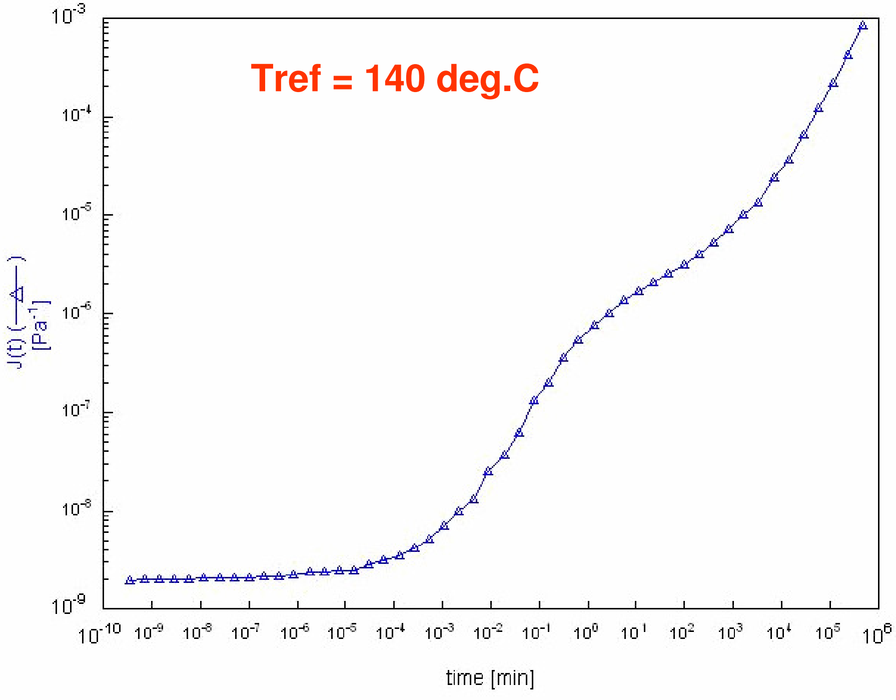
- The modulus master curves from the parallel plate and rectangular torsion tests can be combined at the reference temperature to show the transition from melt to rubber to glass.

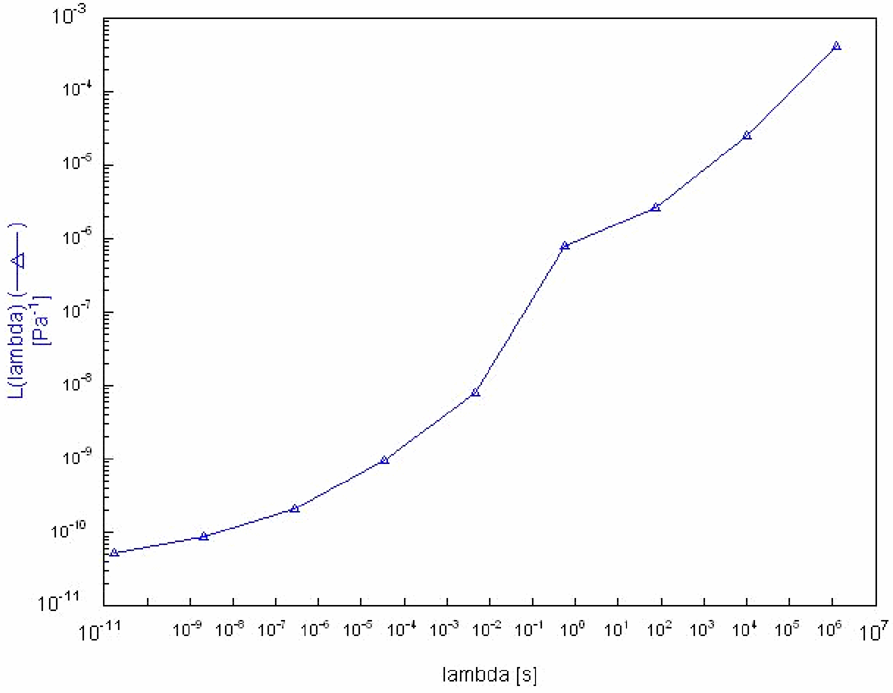


Retardation spectrum

- The modulus (G) master curve can be transformed to the compliance (J) master curve and then to the retardation spectrum

Dynamic data → Retardation Spectrum



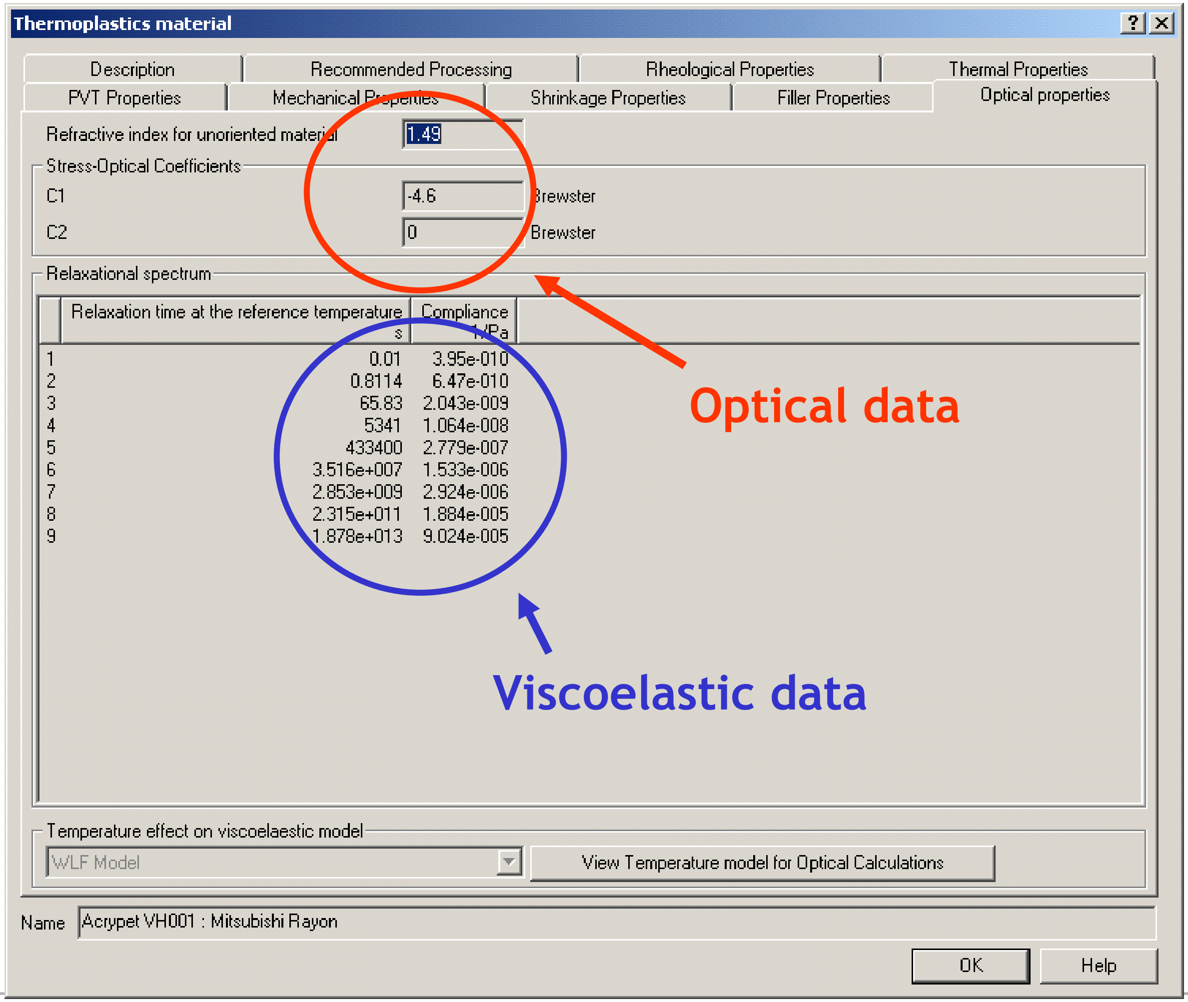


Temperature Shift

- Shows how the retardation spectrum changes for different temperatures
- May use WLF from the melt viscosity but…
- More accurate to use its own parameters

$$t_i(T) = t_i(T_{ref})\exp\frac{-A_1(T - T_{ref})}{A_2 + (T - T_{ref})}$$

Birefringence Simulation- Requirements



Refractive index for unoriented material: 1.49

Stress-Optical Coefficients

C1: -4.6 Brewster

C2: 0 Brewster

Relaxational spectrum

	Relaxation time at the reference temperature s	Compliance 1/Pa
1	0.01	3.95e-010
2	0.8114	6.47e-010
3	65.83	2.043e-009
4	5341	1.064e-008
5	433400	2.779e-007
6	3.516e+007	1.533e-006
7	2.853e+009	2.924e-006
8	2.315e+011	1.884e-005
9	1.878e+013	9.024e-005

Temperature effect on viscoelaestic model: WLF Model

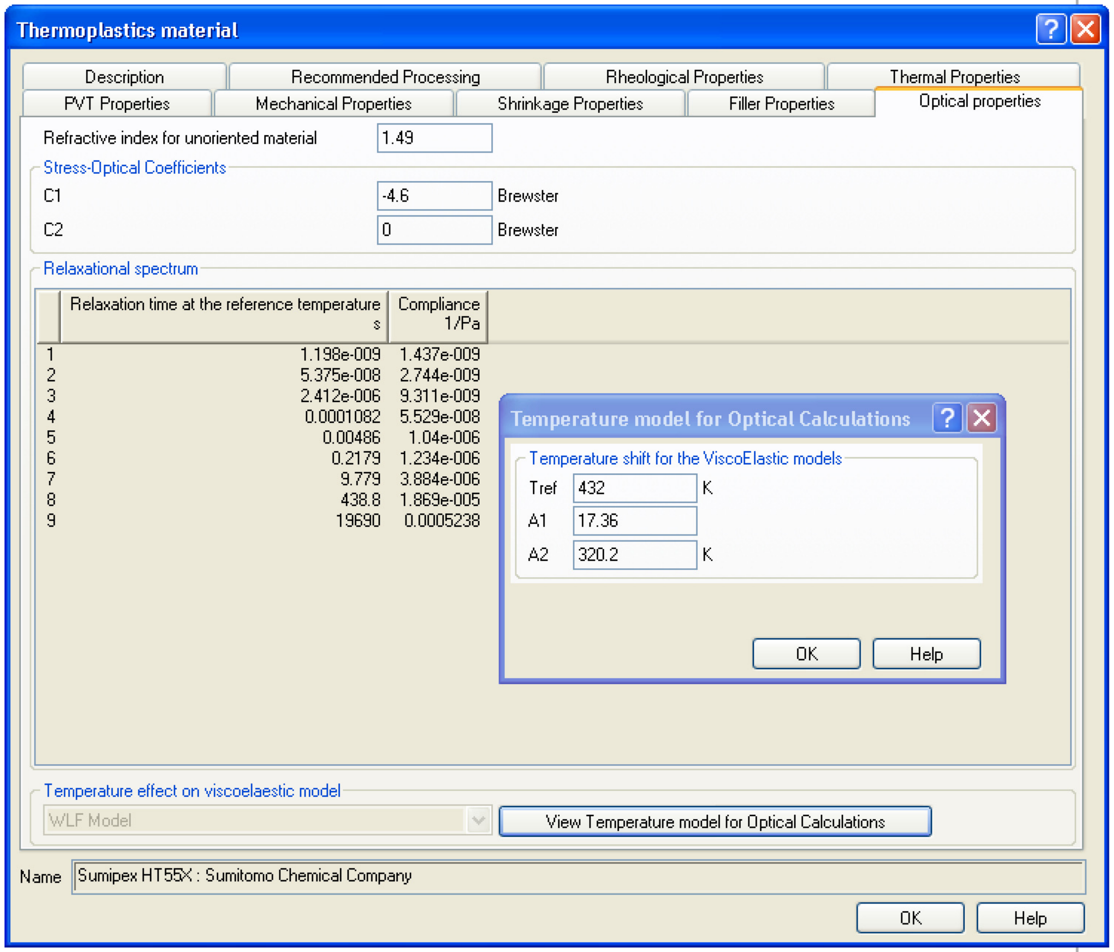
Name: Acrypet VH001 : Mitsubishi Rayon

Optical data

Viscoelastic data

Material Properties for Birefringence Analysis

- Optical properties
  - Base refractive index
  - Stress optical coefficients of the material
- Viscoelastic data
  - Relaxational spectrum
  - Parallel plate rheom.
  - Grade specific data recommended
- Moldflow Plastics Labs offers testing services for this data
- 6 mats tested so far



Refractive index for unoriented material: 1.49

Stress-Optical Coefficients

C1: -4.6 Brewster

C2: 0 Brewster

Relaxational spectrum

	Relaxation time at the reference temperature s	Compliance 1/Pa
1	1.198e-009	1.437e-009
2	5.375e-008	2.744e-009
3	2.412e-006	9.311e-009
4	0.0001082	5.529e-008
5	0.00486	1.04e-006
6	0.2179	1.234e-006
7	9.779	3.884e-006
8	438.8	1.869e-005
9	19690	0.0005238

Temperature model for Optical Calculations

Temperature shift for the ViscoElastic models

Tref: 432 K

A1: 17.36

A2: 320.2 K

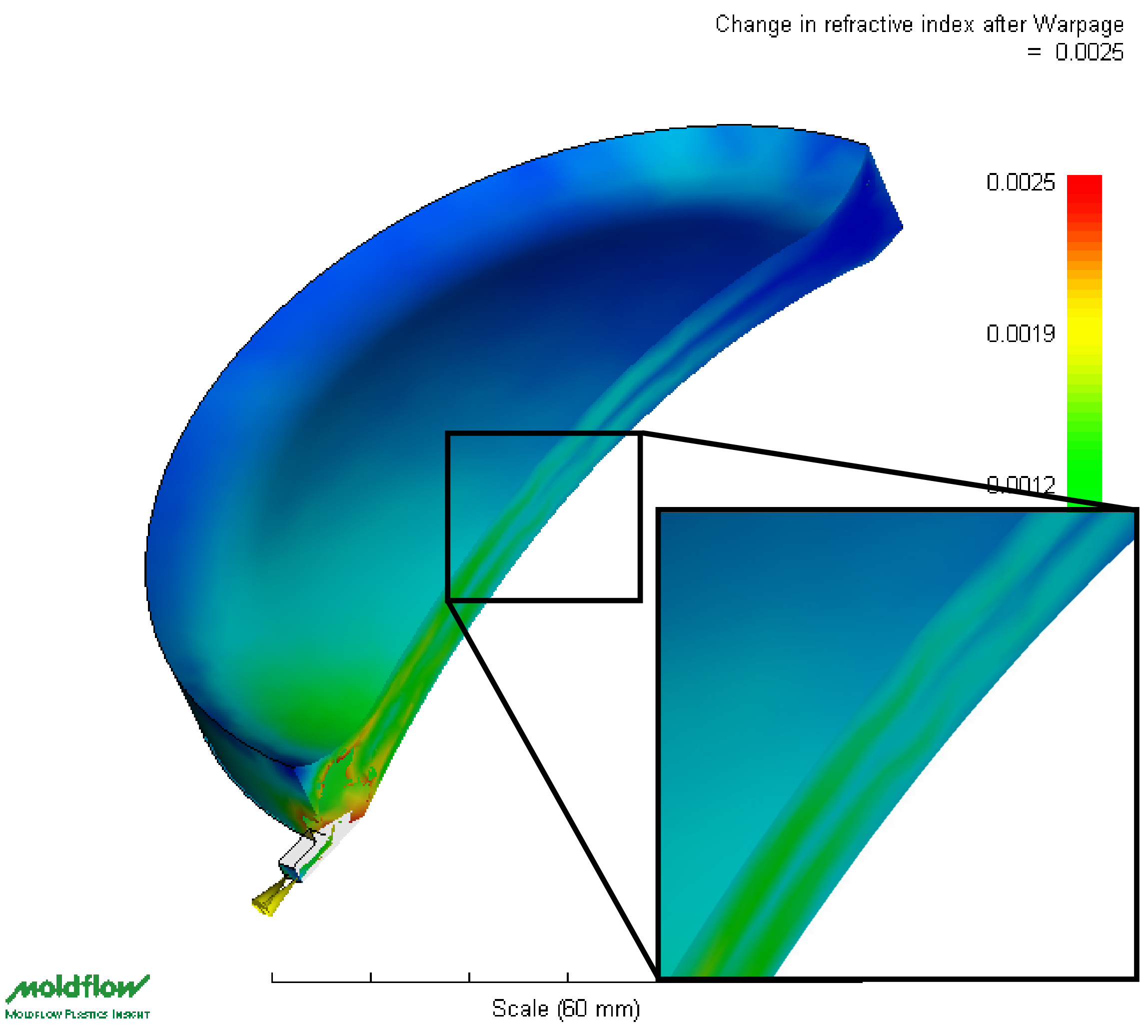
Temperature effect on viscoelaestic model: WLF Model

View Temperature model for Optical Calculations

Name: Sumipex HT55X : Sumitomo Chemical Company

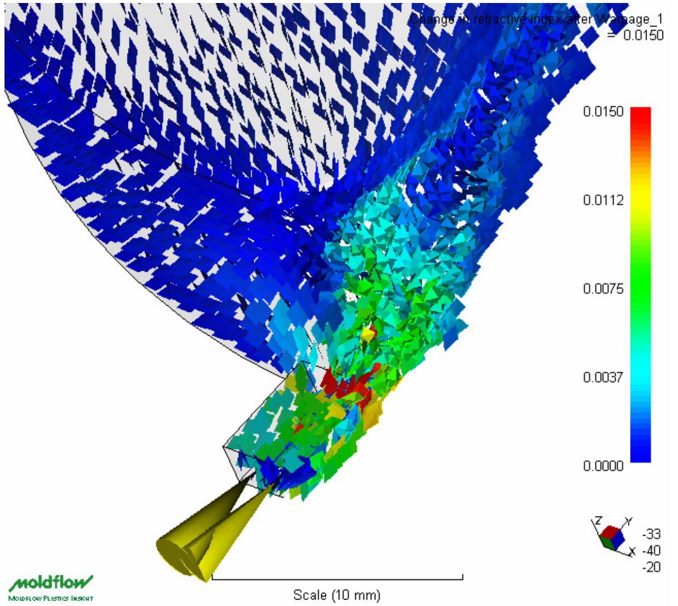
Change in Refractive Index

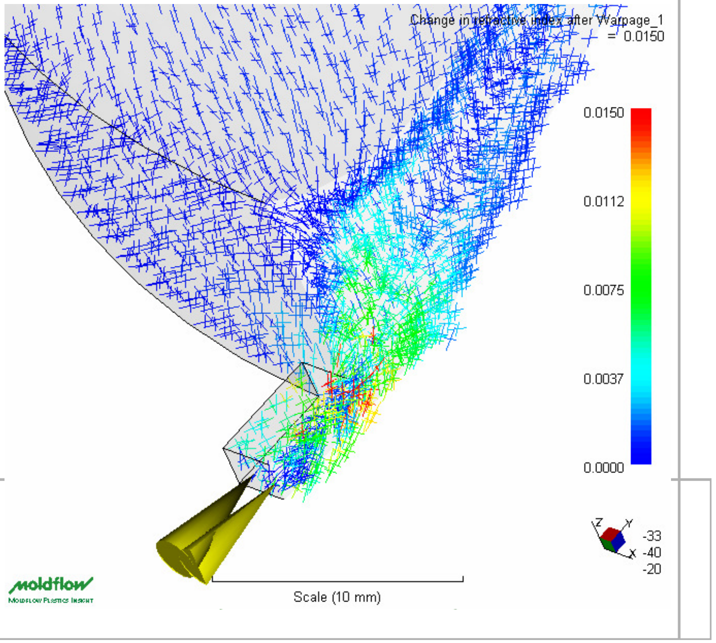
- Difference in refractive index after warpage
- Used to detect changes in refractive index caused by stresses after deformation



Scaled Refractive Index (Cutting Plane)

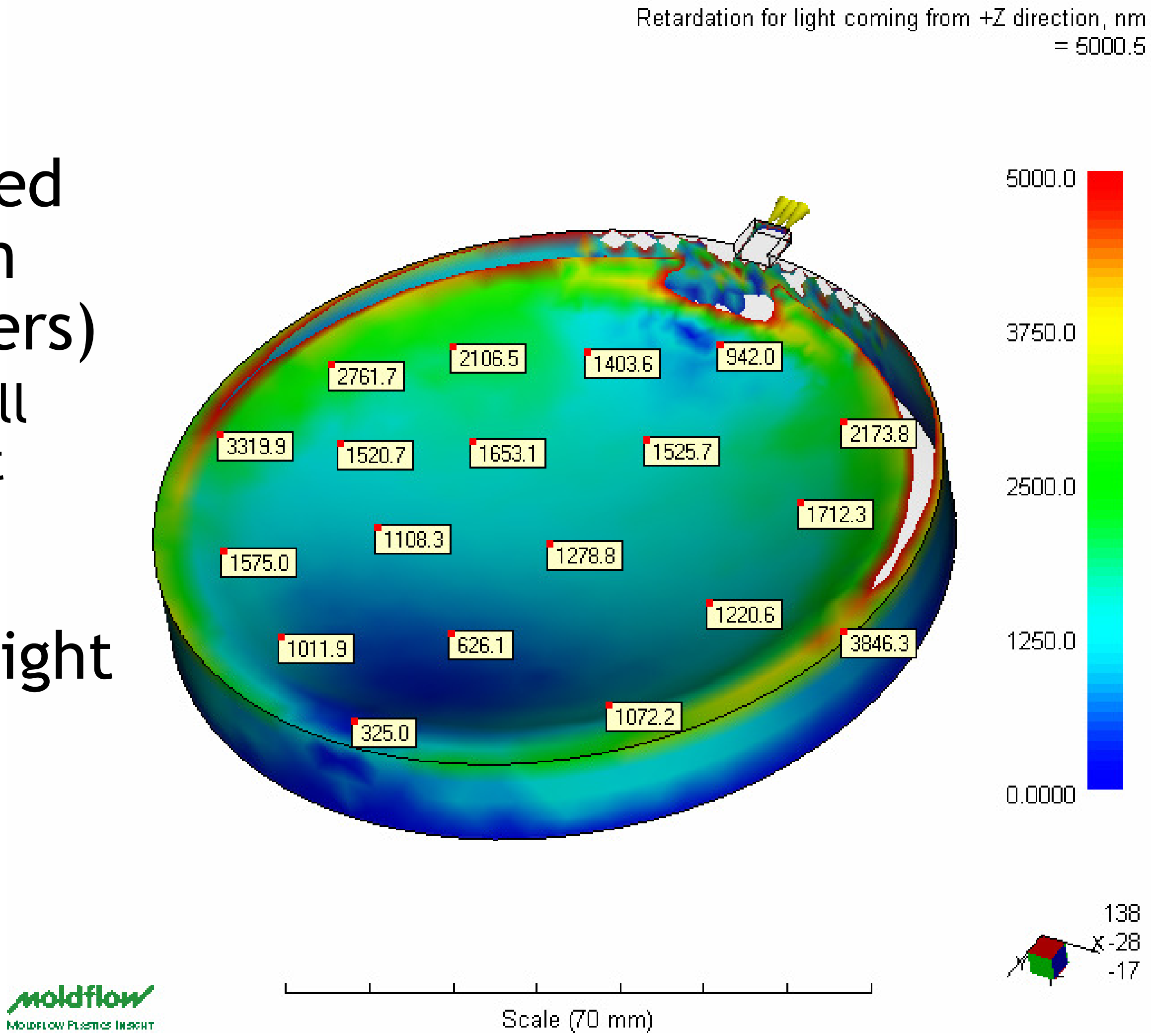
- Birefringence when tensors in principle directions vary
- Double image
  - If the change in refractive index tensor has no axis along the direction of the incident light
- Polarisation effect (color bands)
  - If one of the axes of the change in refractive index tensor is parallel to the incident light the polarisation of the light will change.





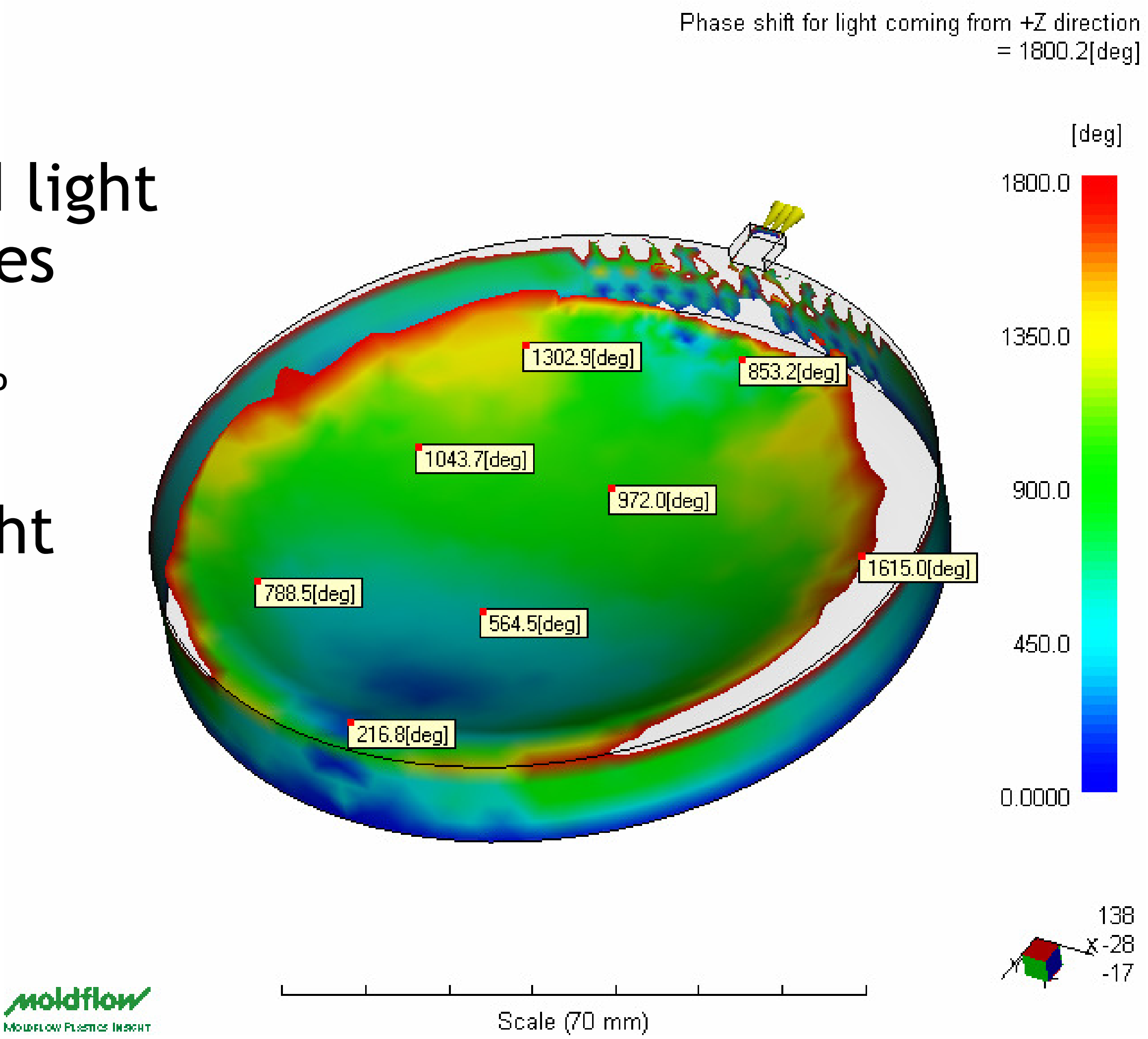
Retardation

- Difference in horizontally and vertically polarised light expressed in length (nanometers)
  - Max should be well under 25% of light wavelength often less (10%)
- Result based on light direction



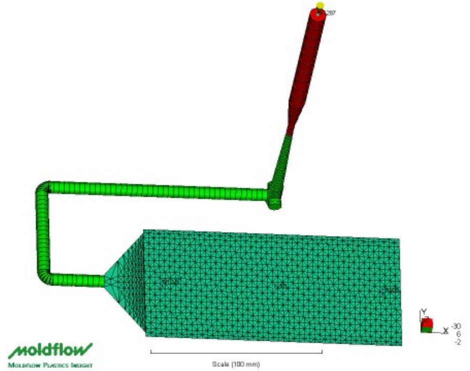
Phase Shift

- Difference in horizontally and vertically polarised light expressed in degrees
  - Max should be well under 360º often 90º or lower is a limit
- Result based on light direction

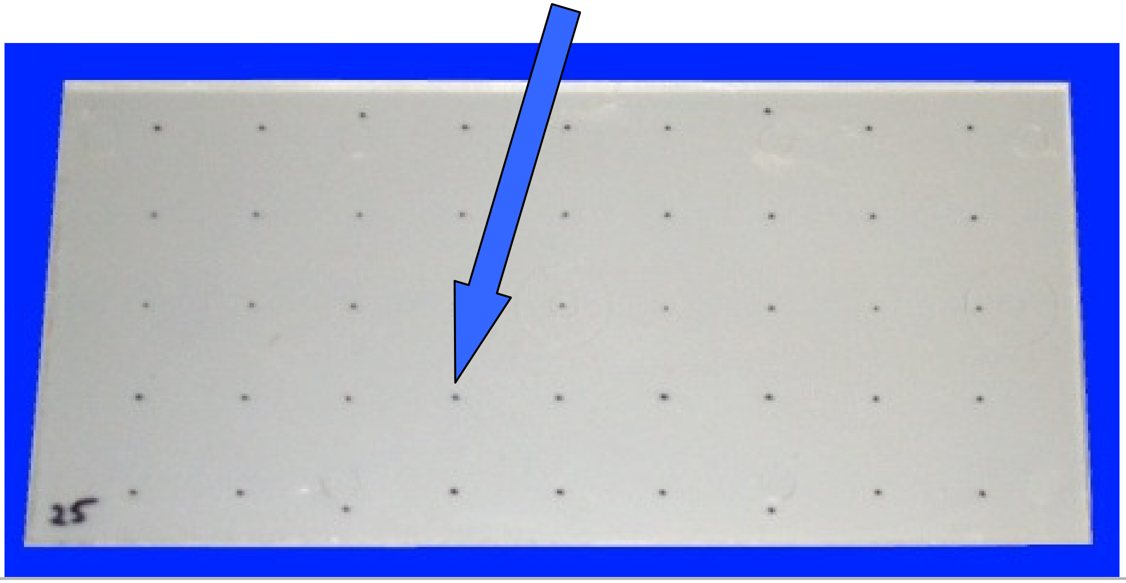


Retardation Measurement Process #1

- Retardation is measured by the Berek compensation technique
- Retardation is measured at 45 points (9x5 grid) offset from cavity edges
- Identical samples are stacked three or more high for greater accuracy
- Reported results are an average for a single sample



Measurement point

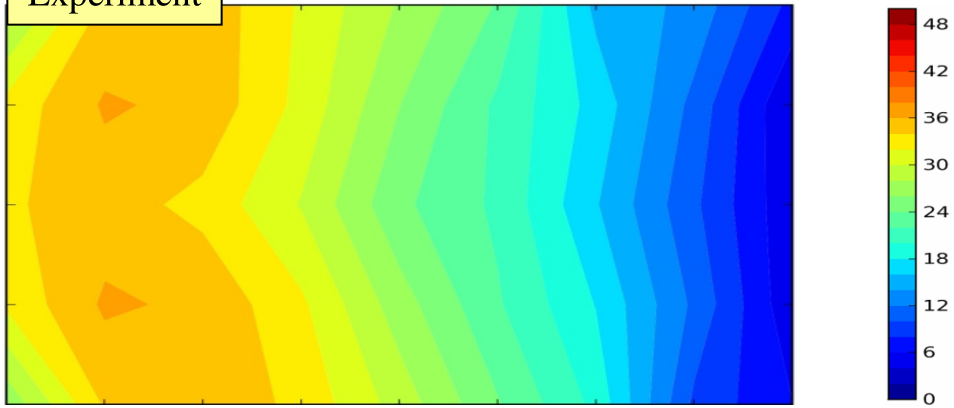


Flow

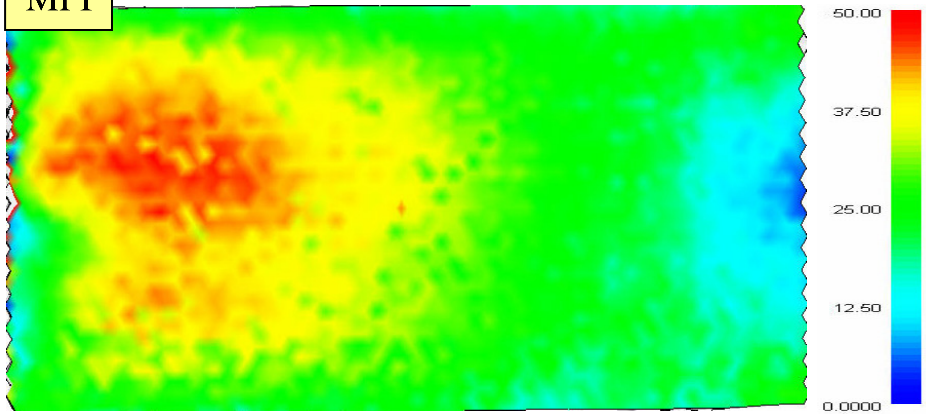
Retardation Validation - PMMA

Case 4: 3mm cavity, slow fill

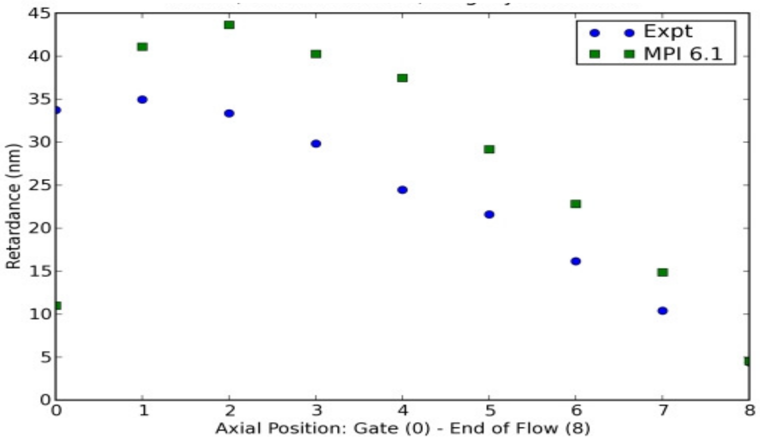
Experiment



MPI



Retardation along Centerline

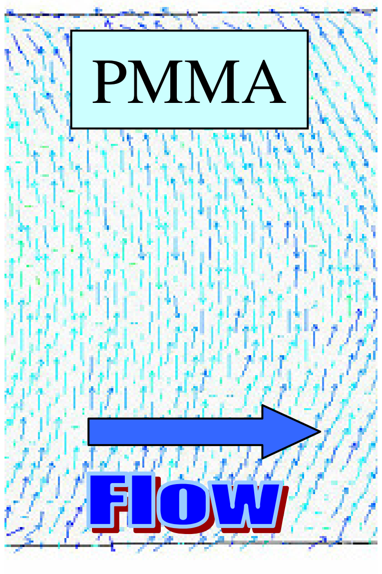


Maximum Measurement Uncertainty
0.72 nm (95% CI)

Reasonable agreement between experiment and MPI

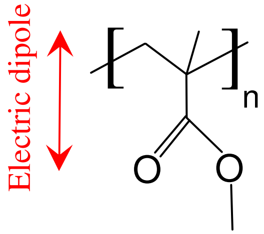
Birefringence Orientation Validation

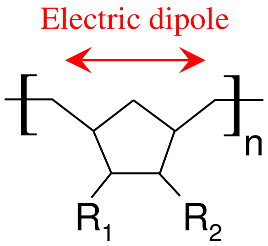
MPI tensor plots of 1st principal component of retardance tensor

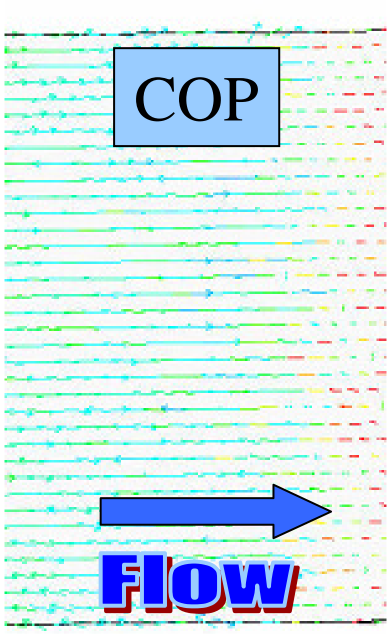


Experimental Orientation Result for PMMA

Observed direction of maximum birefringence is **transverse** to flow







Experimental Orientation Result for COP

Observed direction of maximum birefringence is **aligned** with flow

Viscoelastic data

- Viscoelastic data is used for birefringence predictions
- The data allows the simulation of the evolving refractive index during the moulding of optical components
- In the future the use of viscoelastic data is likely to be more widespread

Future Work & Challenges

- Flow of high performance polymers
  - Liquid Crystal polymers
  - Use viscoelastic data to measure response in melt & solid
- Crystallinity effects
- Optical
  - Birefringence
  - Surface finish
- Strength
  - Performance under load
- Impact resistance
- Electrical
- Effect of colour on shrinkage
- Rapid cooling PVT data
- PVT for Reactive materials