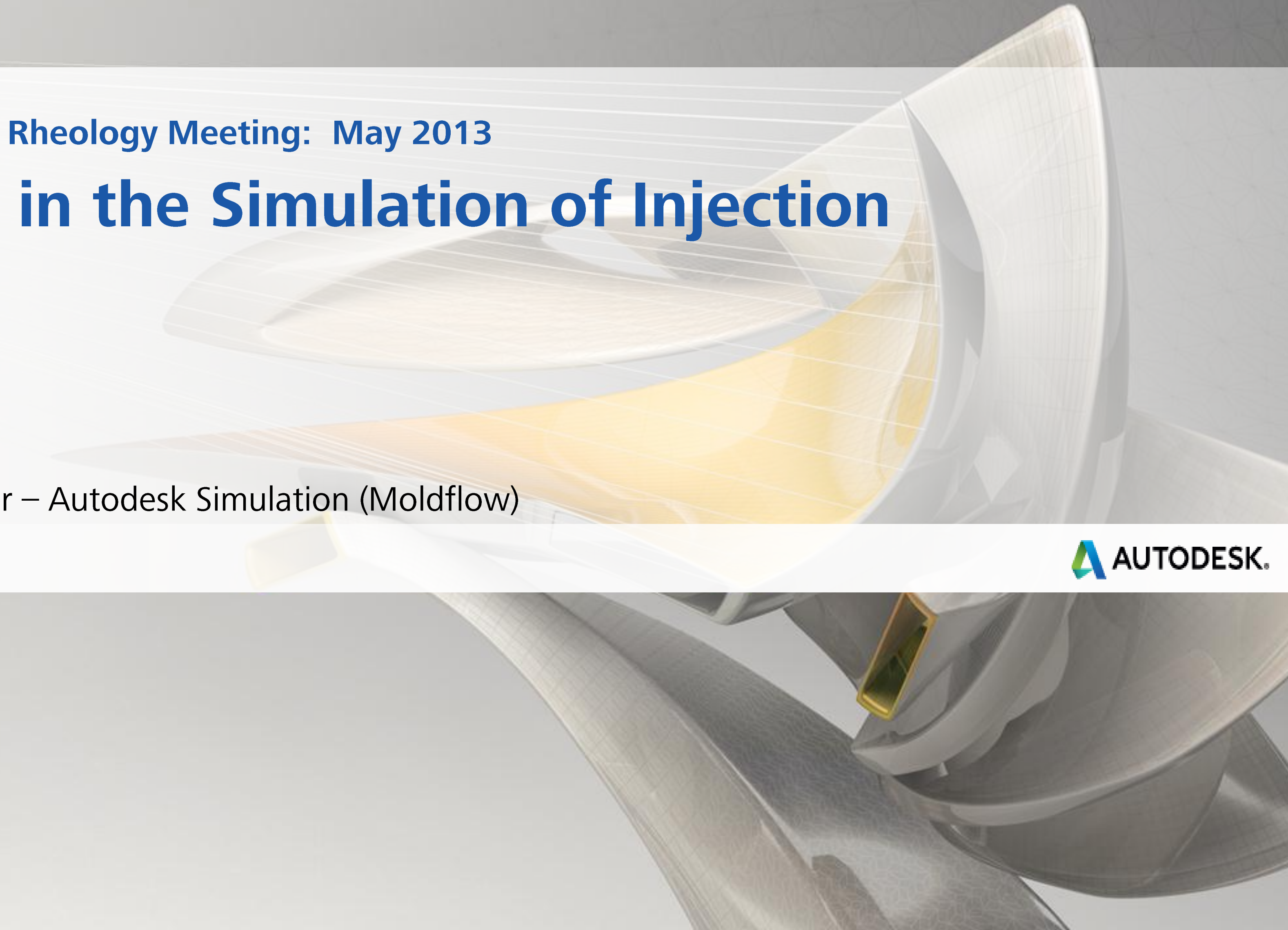
Autodesk Society of Rheology Meeting: May 2013

Challenges in the Simulation of Injection Molding

Dr. Franco Costa

Senior Research Leader – Autodesk Simulation (Moldflow)



Content

- Autodesk Simulation Overview
  - Product Overview
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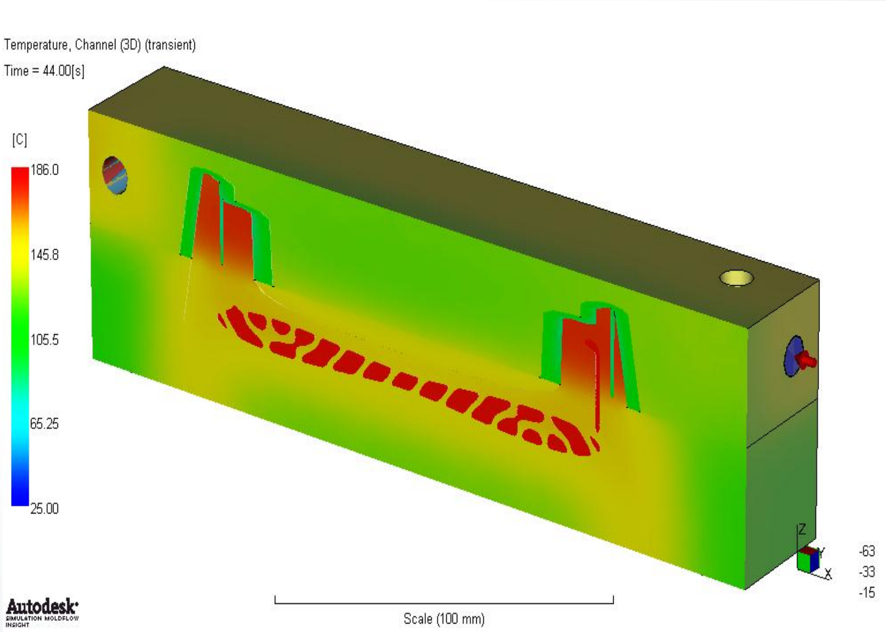
- Some Recent Advances
  - Long Fiber Breakage
  - Crystalline Morphology
  - Stress Relaxation
- Some Tough Problems
  - Micromolding
  - Flow imbalances + Ear-flow
  - Jetting Flows
  - Tiger Stripes



Autodesk Simulation Investments

$500M+
Simulation
Investment

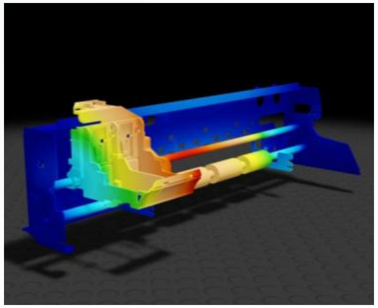
230+ Direct
Development
Staff

2005

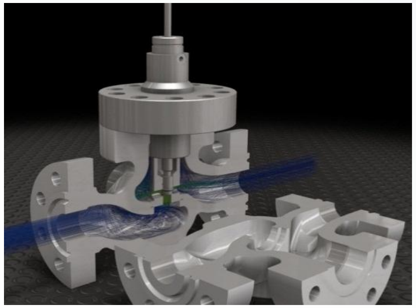
Today

Note: Graphic reflects both technology and company acquisitions, ownership of parent company is not implied

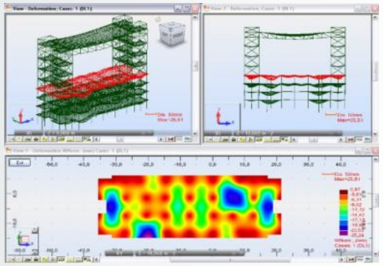
FEA



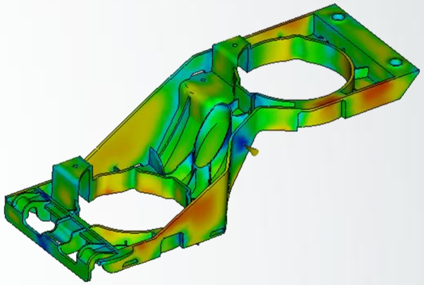
CFD



Structural / Code Checking



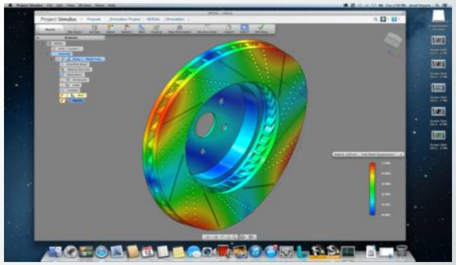
Manufacturing



Test and Validation

Mobile

Cloud



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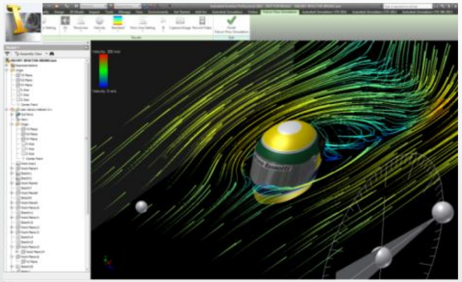
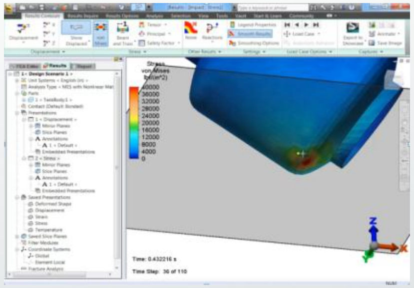
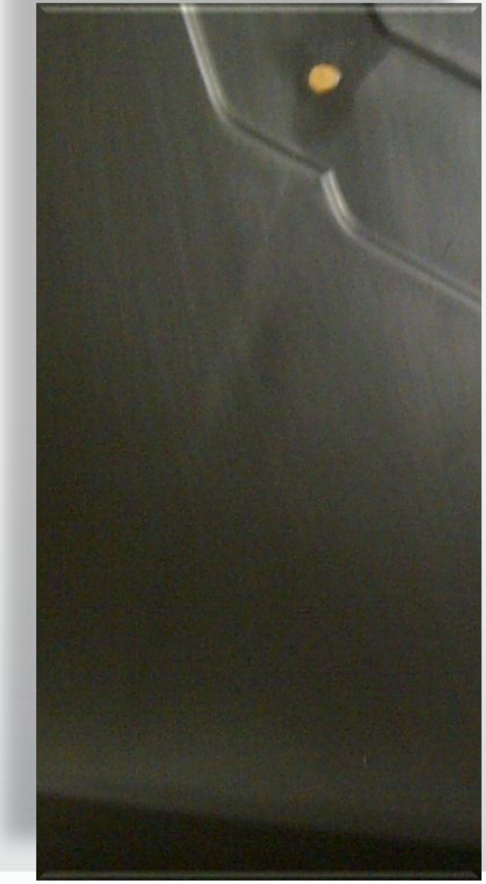


Desktop



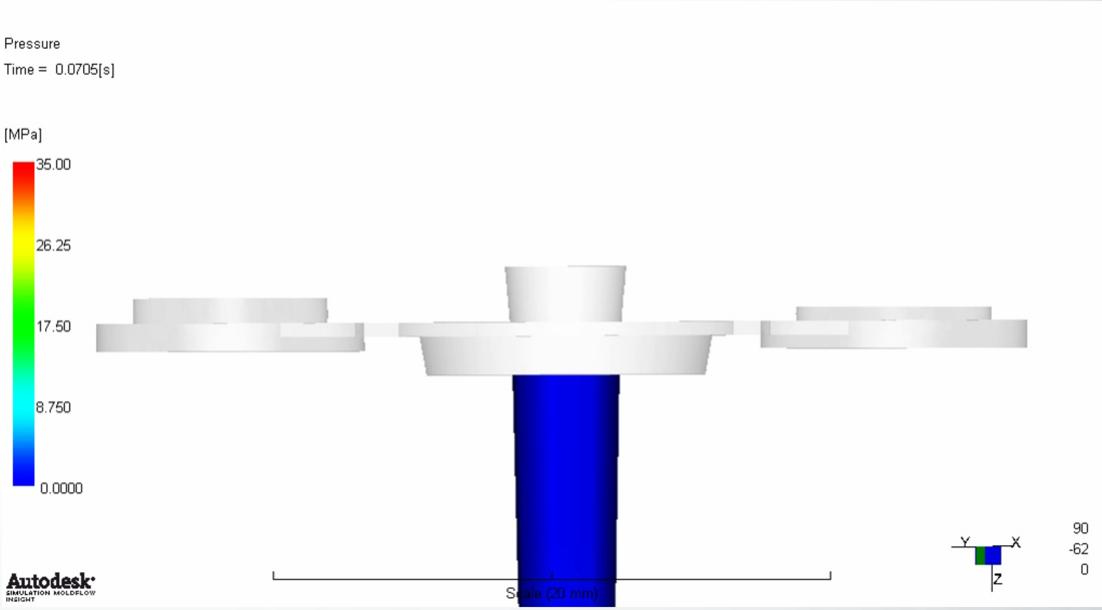
Injection Molding

- Unlike other processes, may not be able to overcome problems with change of process conditions
- Simulation adds high value



Plastic Flow Simulation

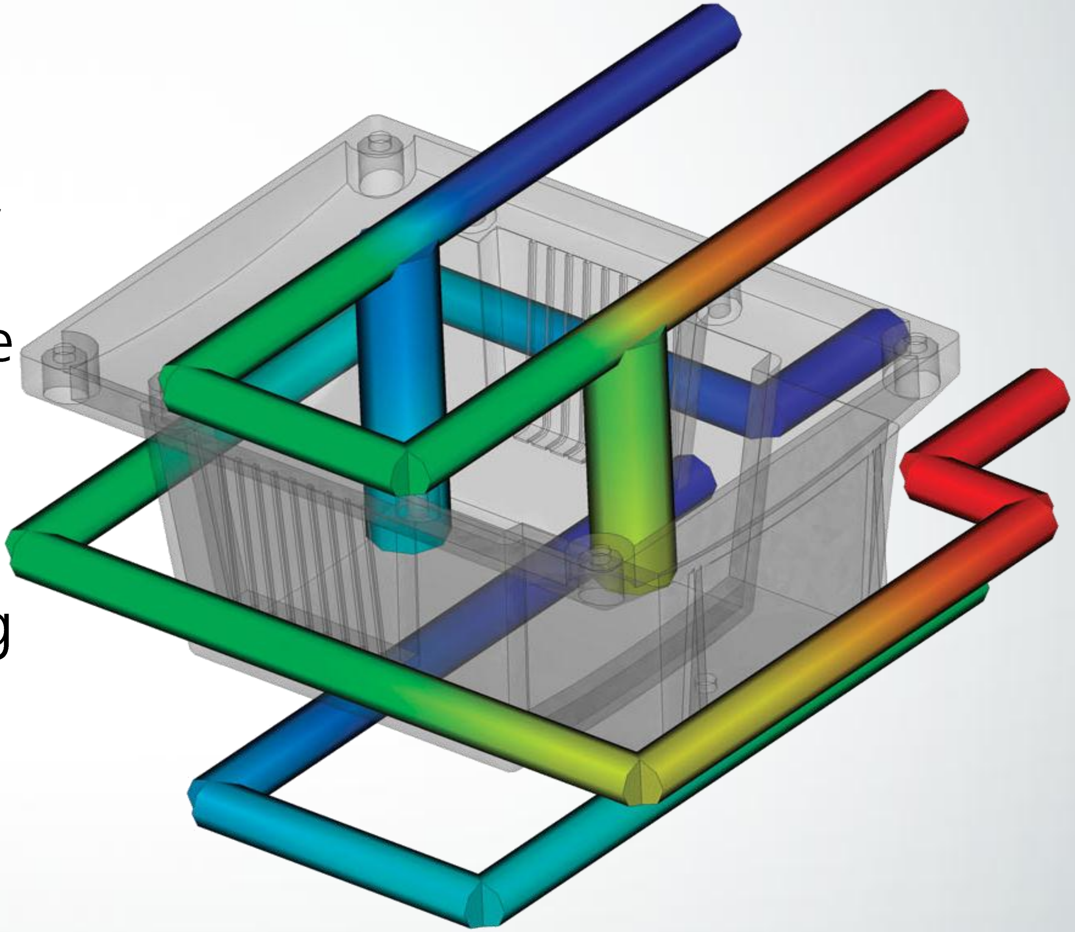
Simulate the flow of melted plastic to help optimize part and mold designs, reduce potential part defects, and improve the molding process



Features

- Filling and Packing Analysis
- Molding Window Analysis
- Design of Experiments
- Insert Overmolding
- Two-Shot Sequential Overmolding
- Compression and Injection-Compression Molding

Mold Heating & Cooling Simulation



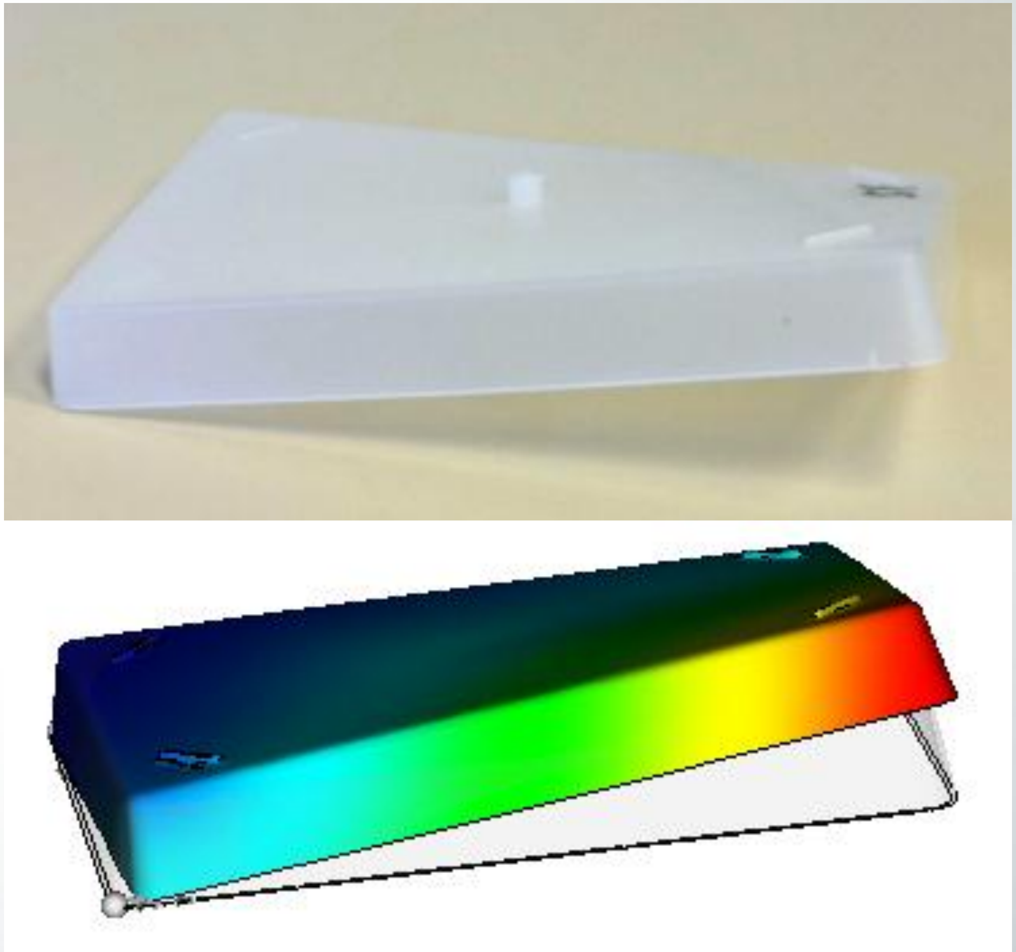
Improve cooling system efficiency, minimize part warpage, achieve smooth surfaces, and reduce cycle times

Features

- Cooling Component Modeling
- Cooling System Analysis
- Rapid Heat Cycle Molding

Shrinkage and Warpage Simulation

Predict and control post-molding shrinkage and warpage and evaluate the structural integrity of the molded part



Features

- Shrinkage Analysis
- Warpage Analysis
- Core Shift Control
- Fiber Orientation

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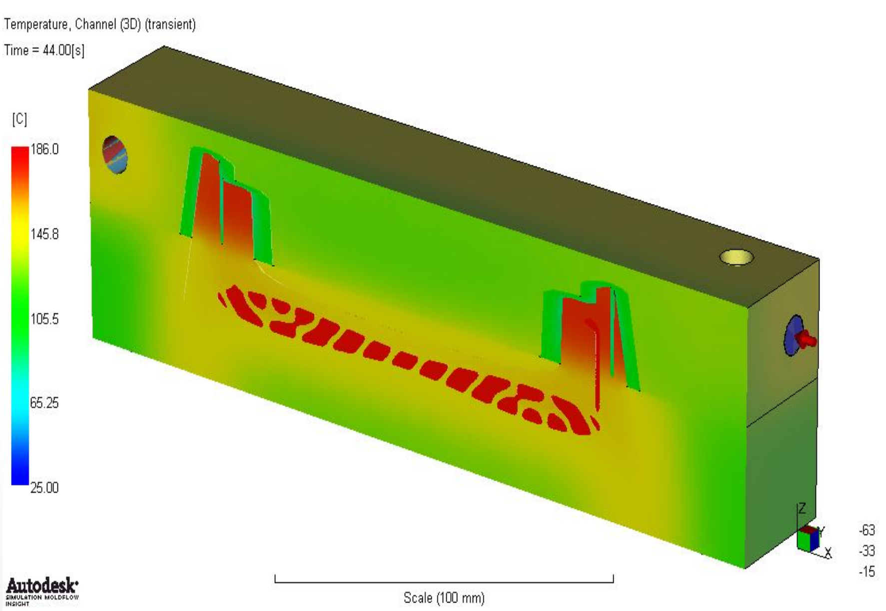
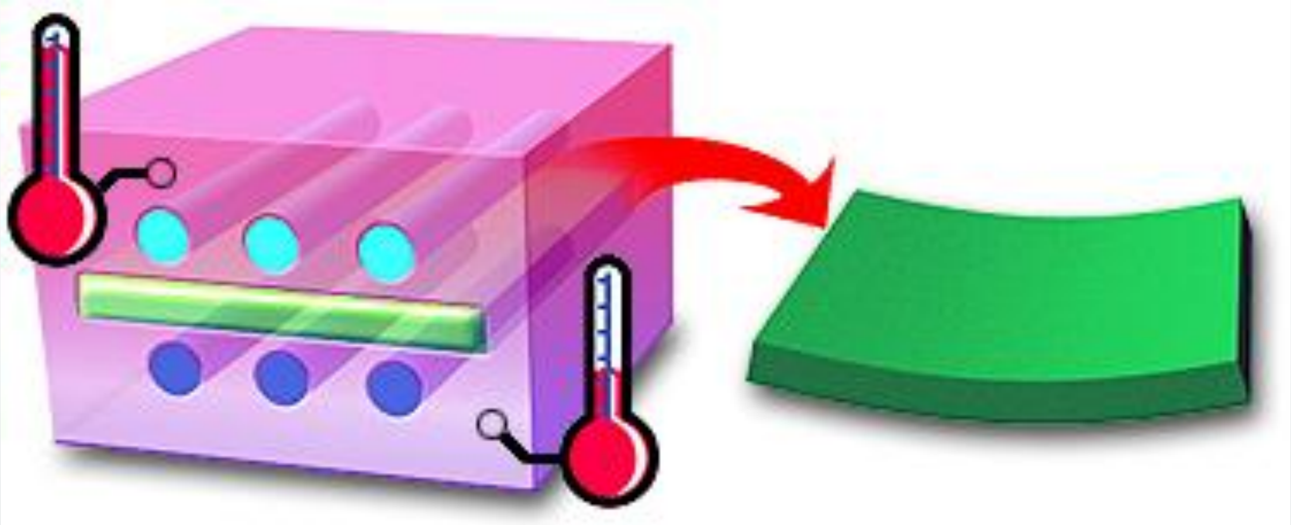


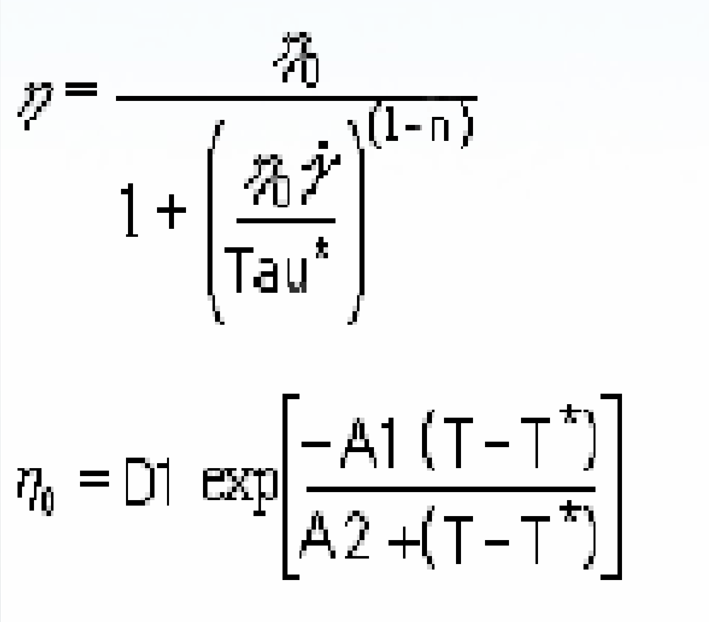
Viscosity in Injection Molding

- Injection pressures range from 0-200MPa
- Shear rates range from 1-100,000/s
- Temperatures range from melt (300C) to mold (40C)
- The phase change from melt to solid must be identified for residual stress calculations



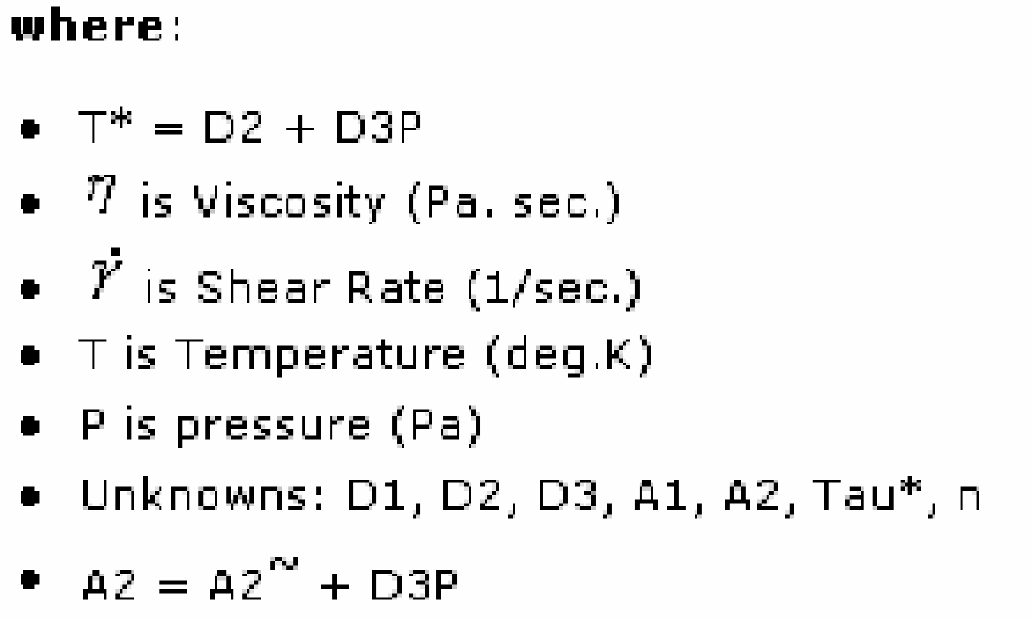
Rheological model - Modified Cross-WLF model

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



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

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

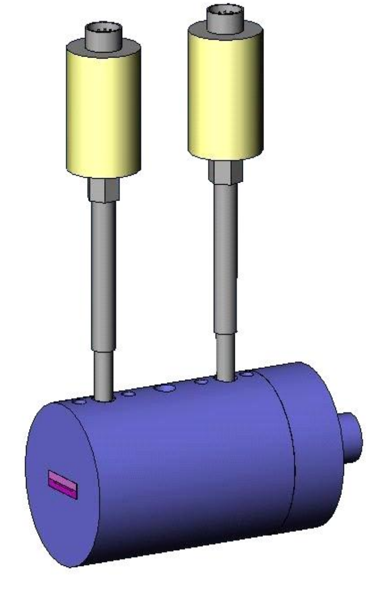


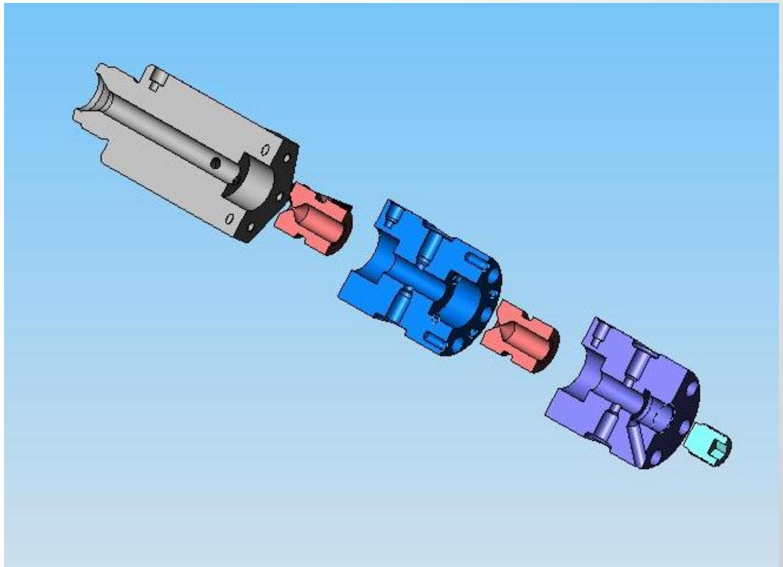
where:

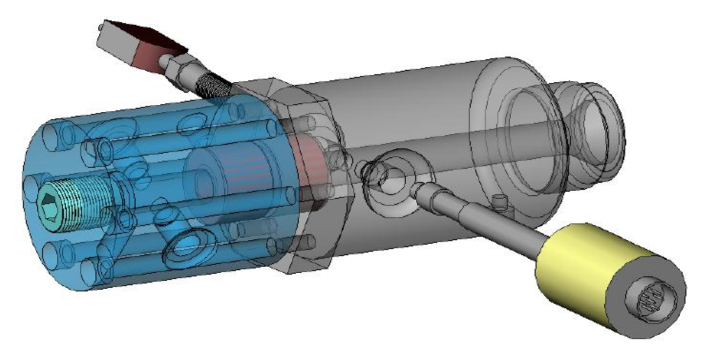
- $T^* = D2 + D3P$
- η is Viscosity (Pa. sec.)
- $\dot{\gamma}$ is Shear Rate (1/sec.)
- T is Temperature (deg.K)
- P is pressure (Pa)
- Unknowns: D1, D2, D3, A1, A2, Tau*, n
- $A2 = A2^{\sim} + D3P$

Rheometer - Design

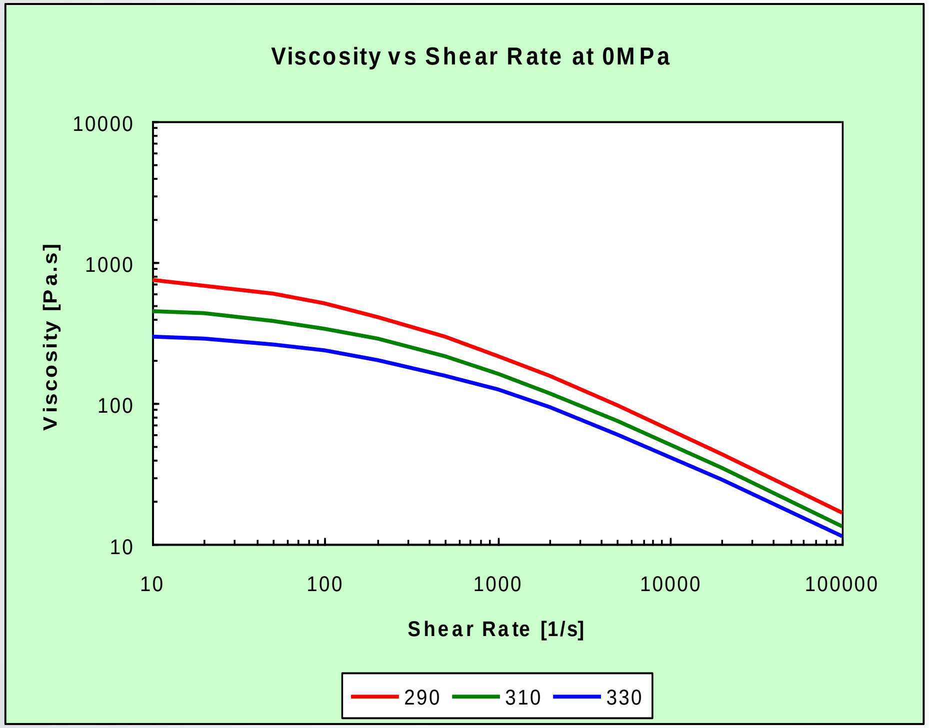
- Many materials are sensitive to the melt preparation conditions
- An inline rheometer prepares the melt under the same conditions used in injection molding (strong thermomechanical history, short residence time)

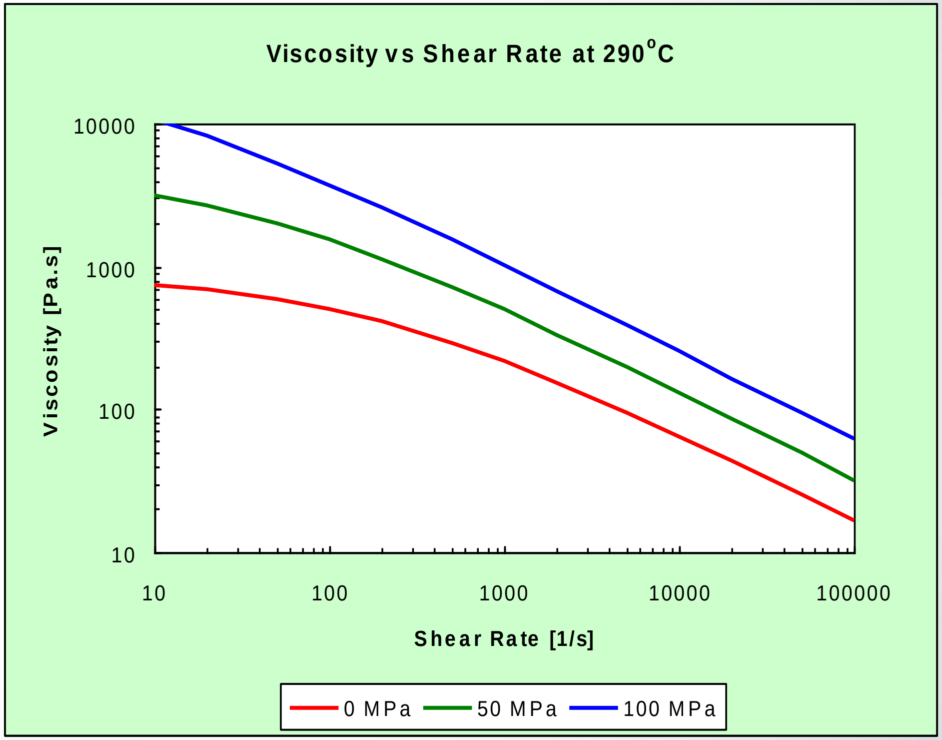






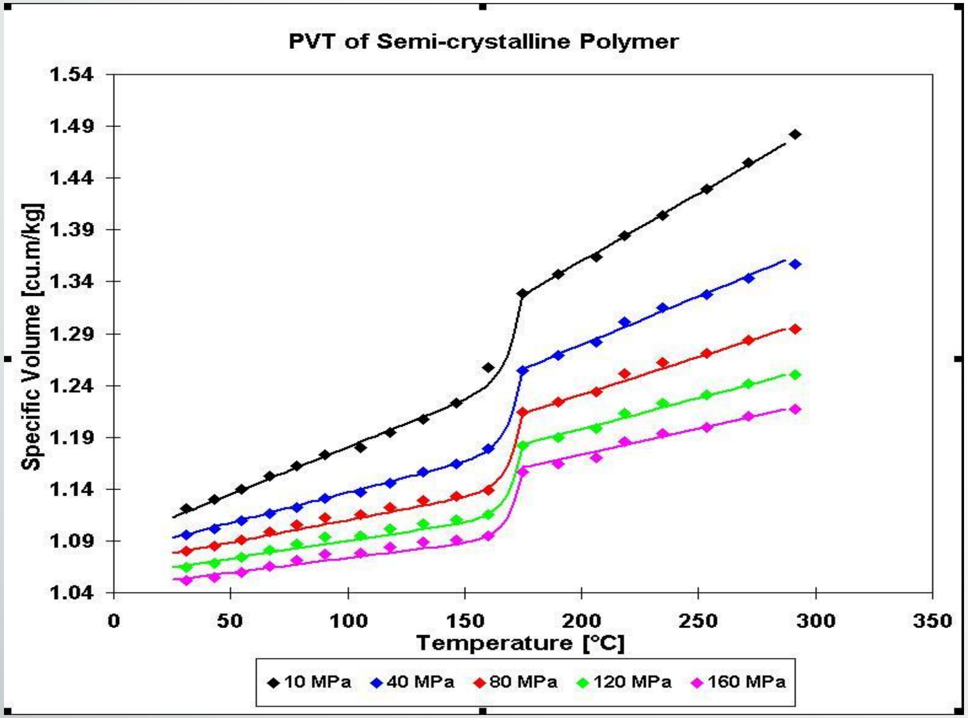
Rheometry – Pressure dependence



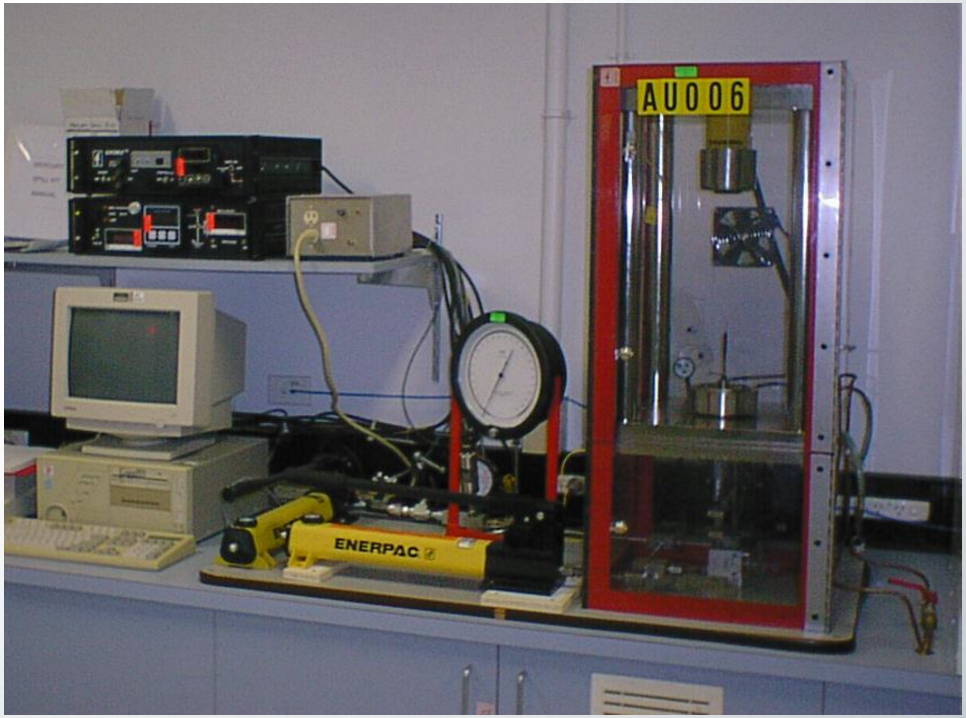


Compressibility - PVT

- Compressibility
  - High pressures involved
    - 0-200 MPa.
  - Materials are compressible

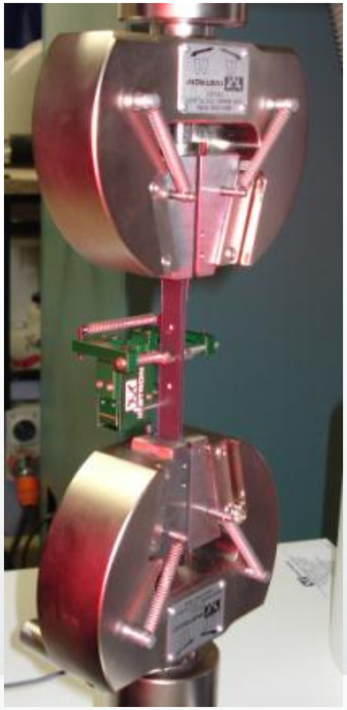


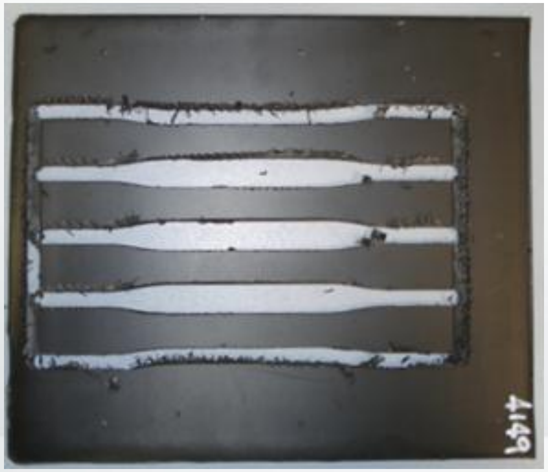
PVT of Semi-crystalline Polymer



Testing Resources

- Injection Molding Machines
- Preparation
- Viscosity
- Thermal
- Pressure-Volume-Temperature
- Mechanical
- Shrinkage
- Viscoelasticity





Injection Molding Machines

Melbourne, Australia

Arburg 35 ton

Arburg 160 ton

Battenfeld 150 ton

Ithaca, NY, USA

Arburg 35 ton

2 * Krauss Maffei 160 ton

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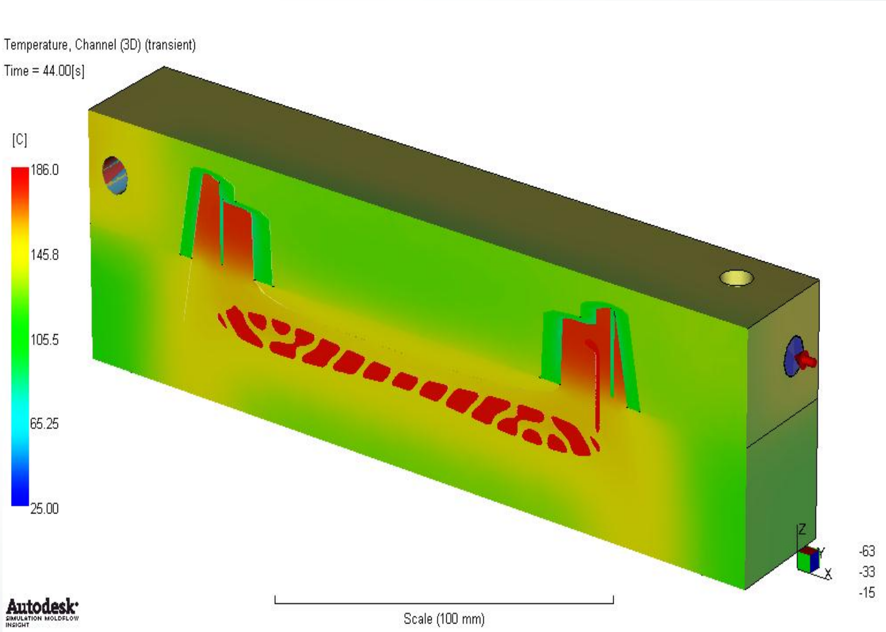
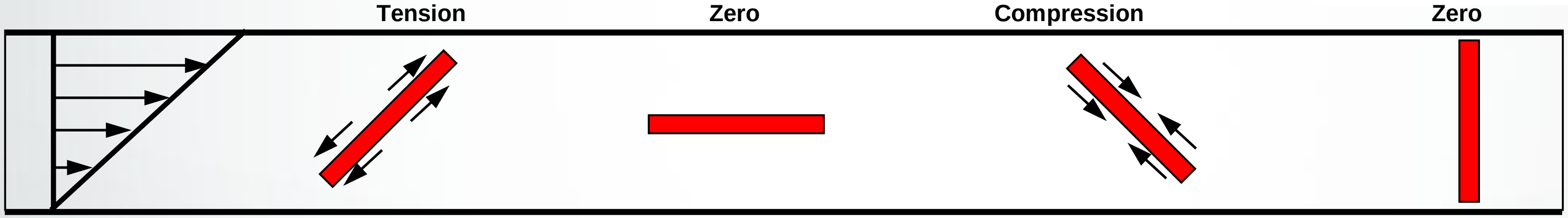


Fiber Breakage Model

- Phelps-Tucker Model
  - Probability of breakage of fibers length l_i

Dinh & Armstrong Model / Critical Buckling Force

$$F_i / F_{crit} = \frac{8 \varsigma \eta_m l_i^4}{\pi^3 E_f d_f^4} (D : A) > 1$$



$$\overline{P}_i = C_b \, \gamma \max\{0, [1 - \exp(1 - F_i / F_{crit})]\}$$

C_b: Strain Rate Coefficient Parameter

ς: Dimensionless Drag Coefficient (Dg)

Fiber Breakage Model

- Probability of creating a fiber of length l_k from a fiber of length l_i

$$R_{ik} = G_{norm}\left(l_i, \frac{l_k}{2}, Sl_k\right)$$

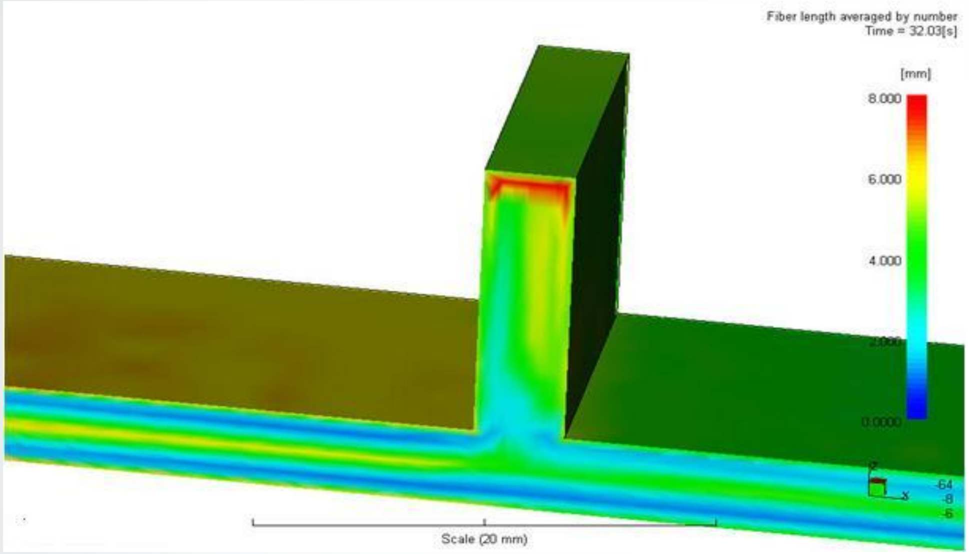
S: Distribution Parameter

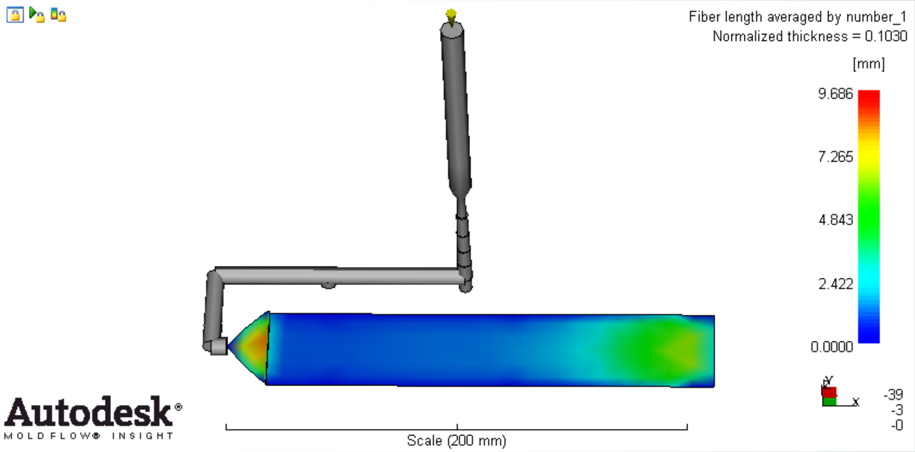
$\overline{N}_{i,t}$: Number of fibers of length l_i which exist at time t

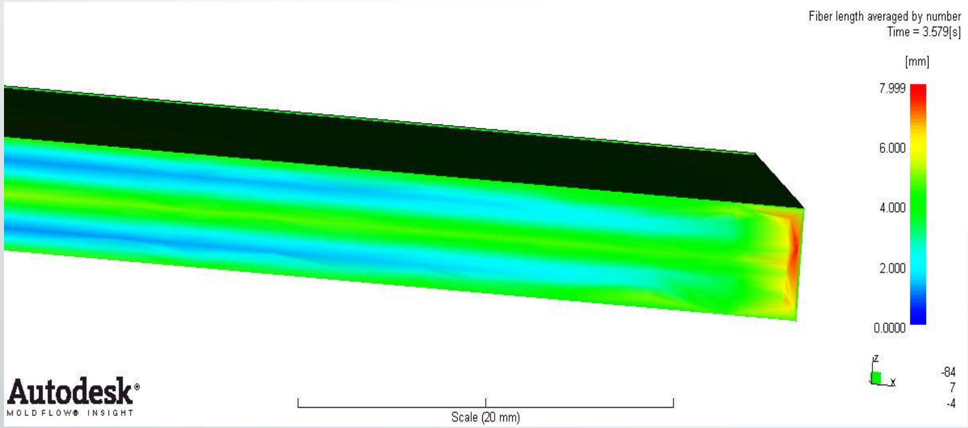
$$\overline{N}_{i,t+\Delta t} = \overline{N}_{i,t} - \overline{P_i}\,\overline{N}_{i,t}\Delta t + \sum_{k|k\geq i}^{M} \overline{R_{ik}}\,\overline{N}_{k,t}\Delta t$$

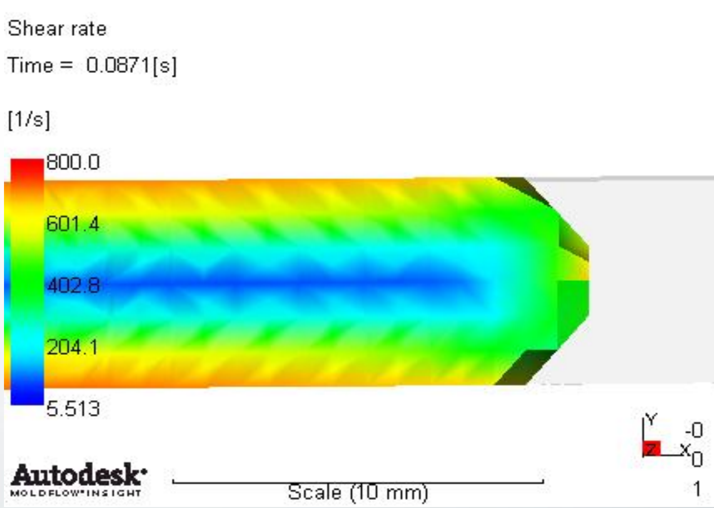
$$i = 1,2,\ldots, M;$$

Fiber Length Distribution in 3D
Some long fibers pushed to the end?

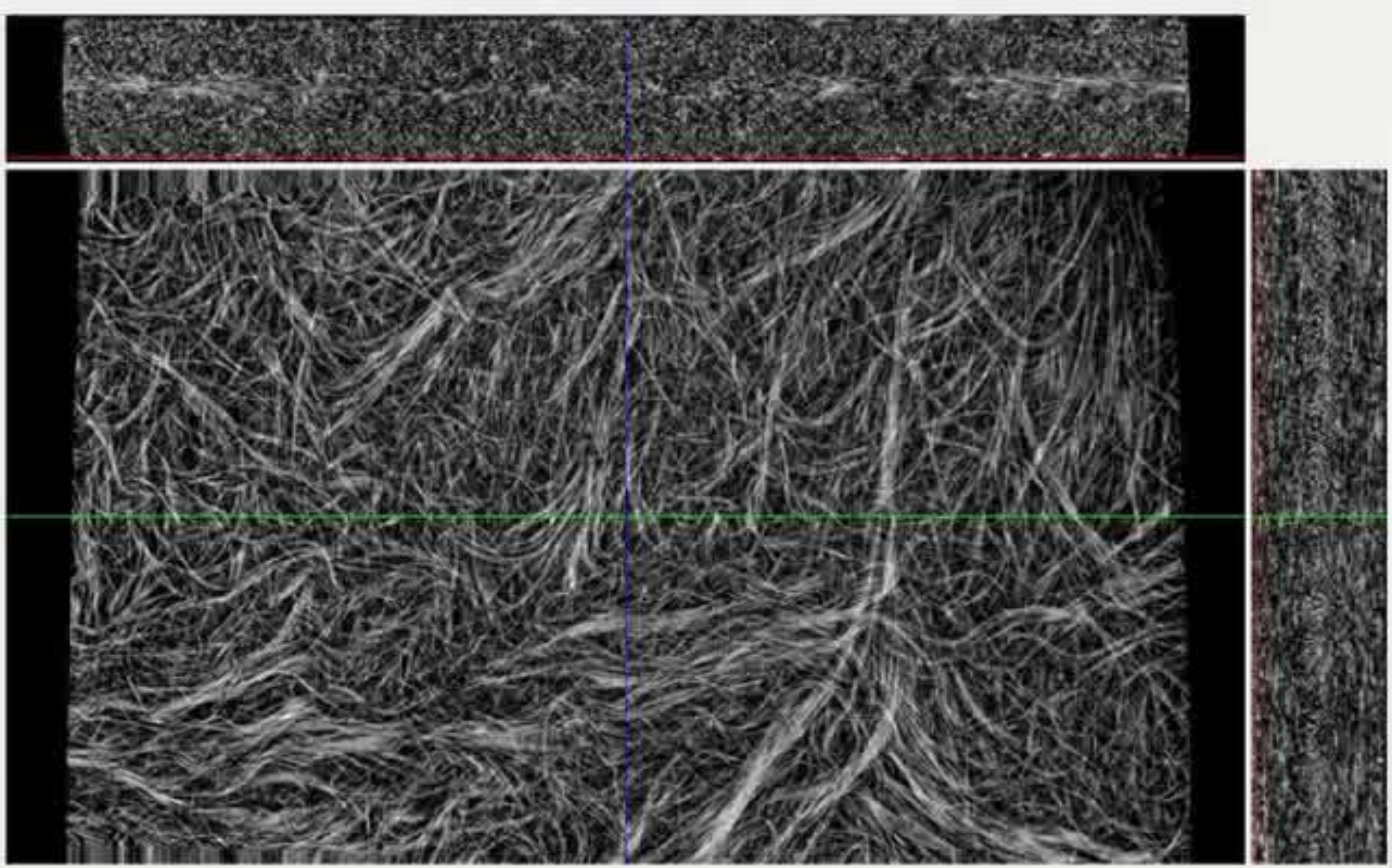






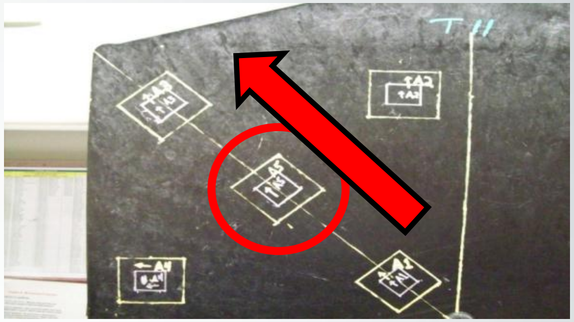


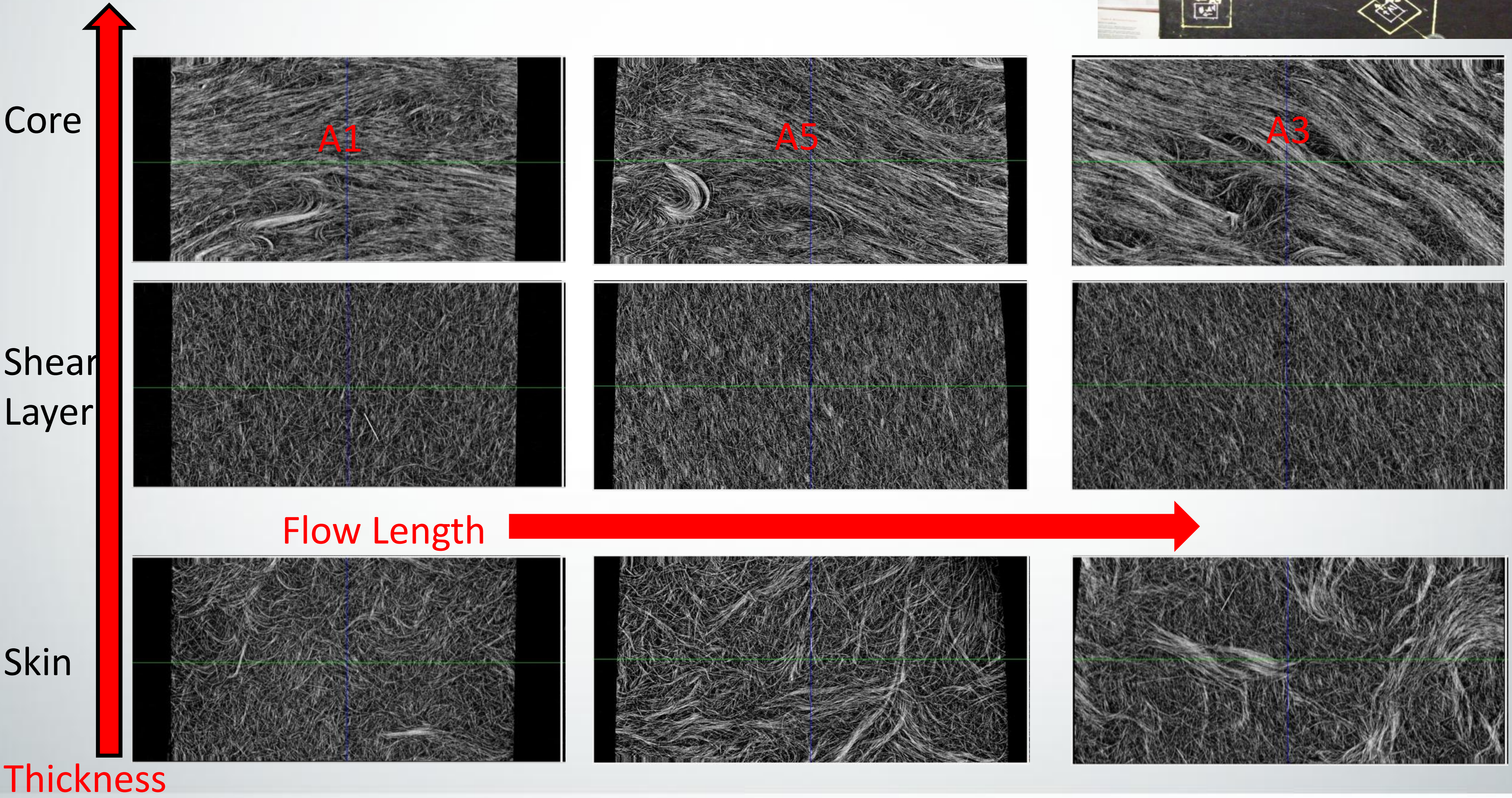
Fiber Length Distribution Measurement & Calculation – Ticona Moldings



Skin

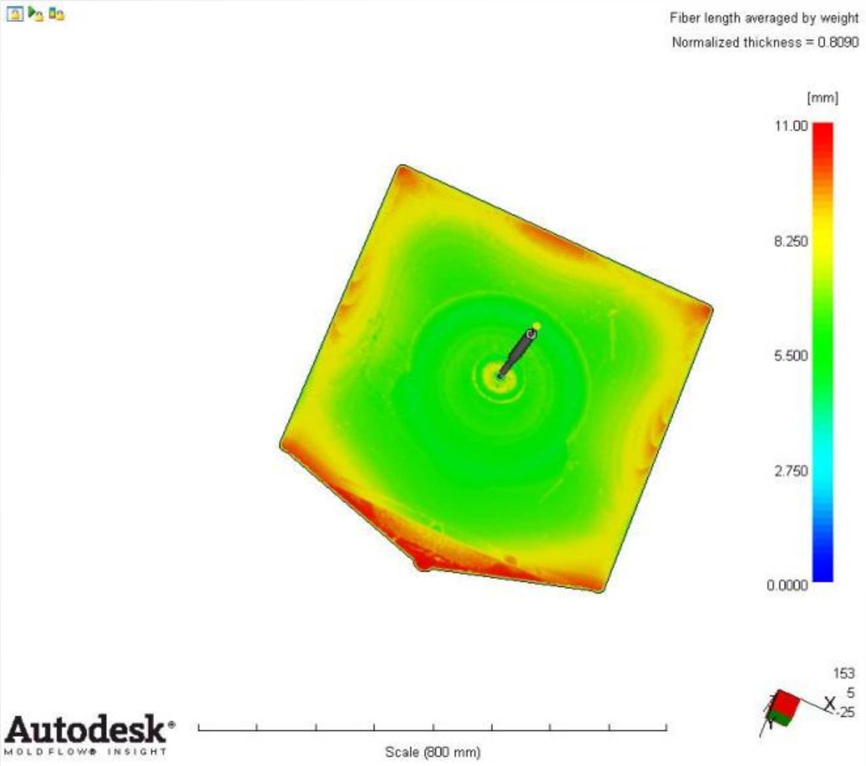
Long Fiber Breakage Model
Fiber Length Evolution



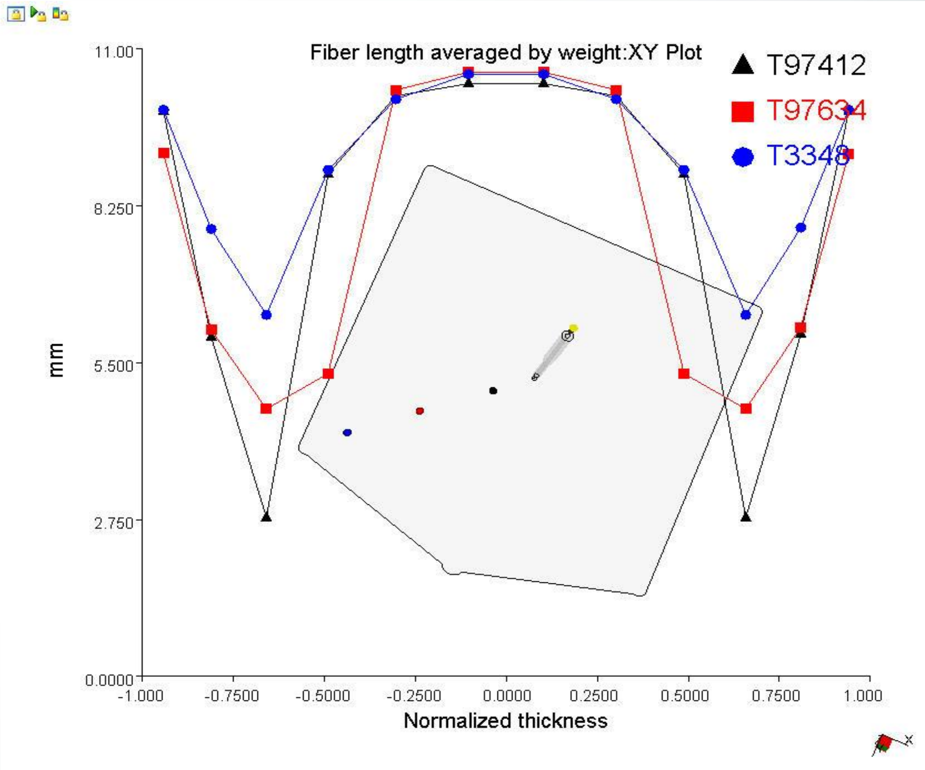


Courtesy: Ticona

Predicted Fiber Length Distributions



Midplane



3D

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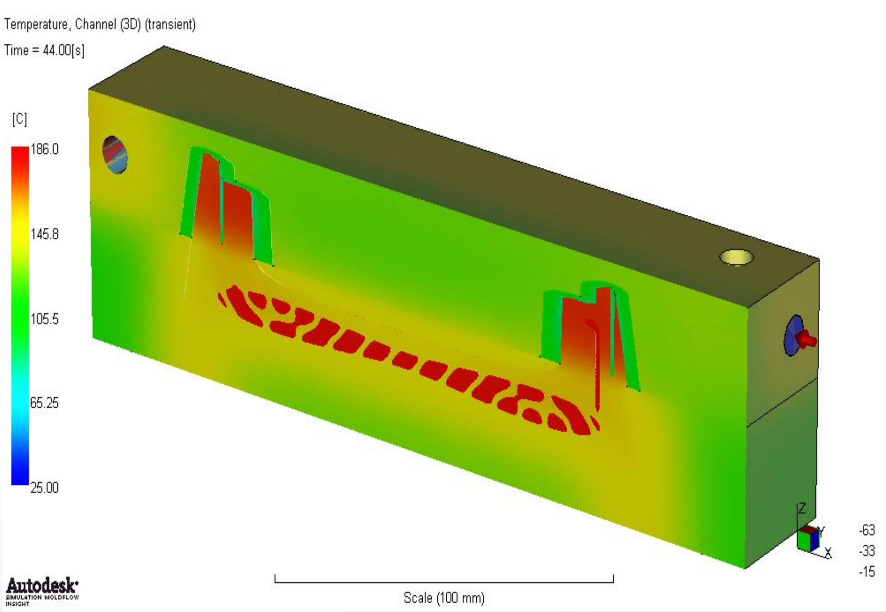
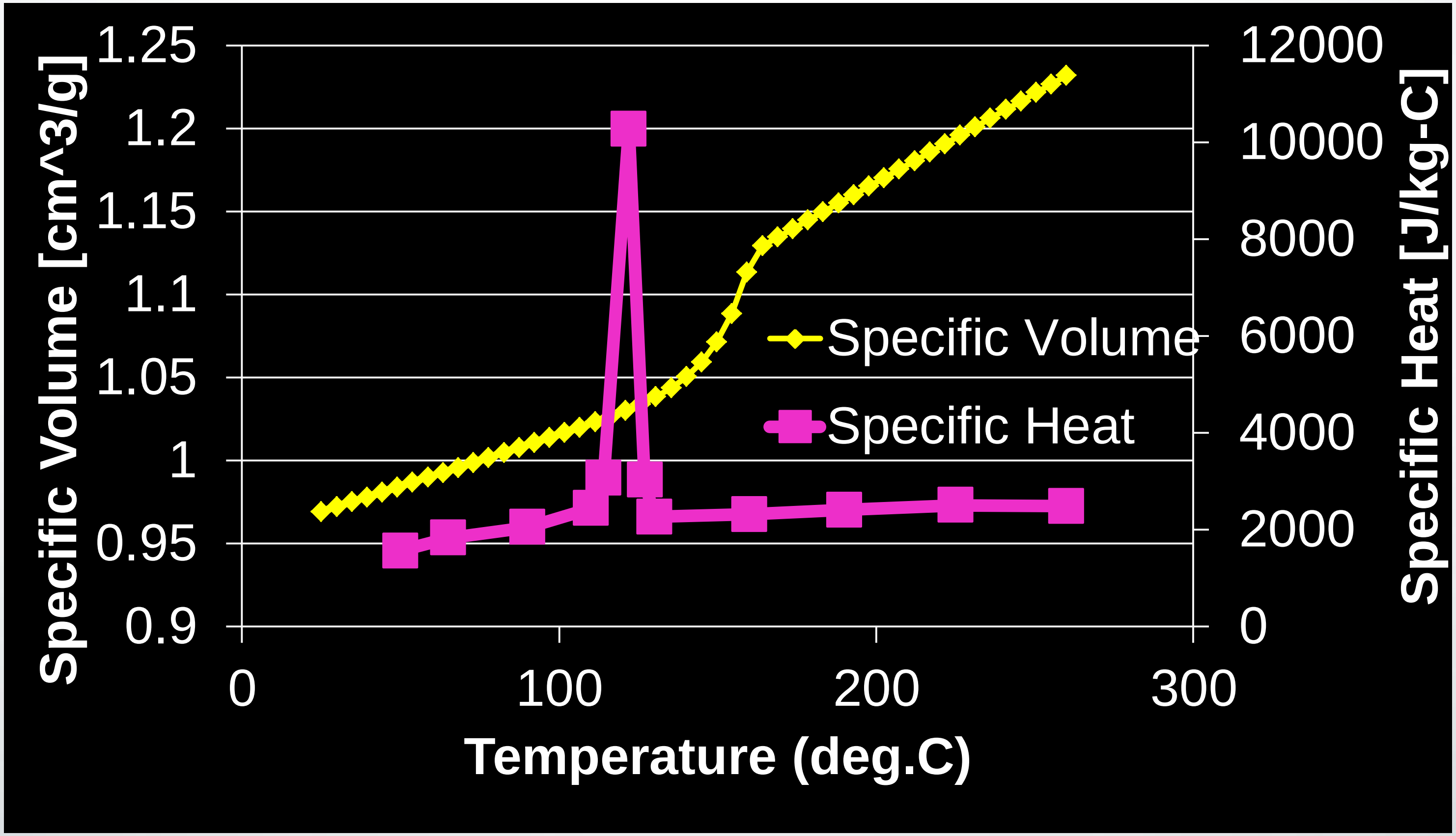


Why Crystallization?

- Solidification
  - Single transition temperature?



PP, 20% talc filled
Sumitomo, Noblen BZE62F5B

Cooling Rate Effect on Solidification

Measured Specific Volume during cooling

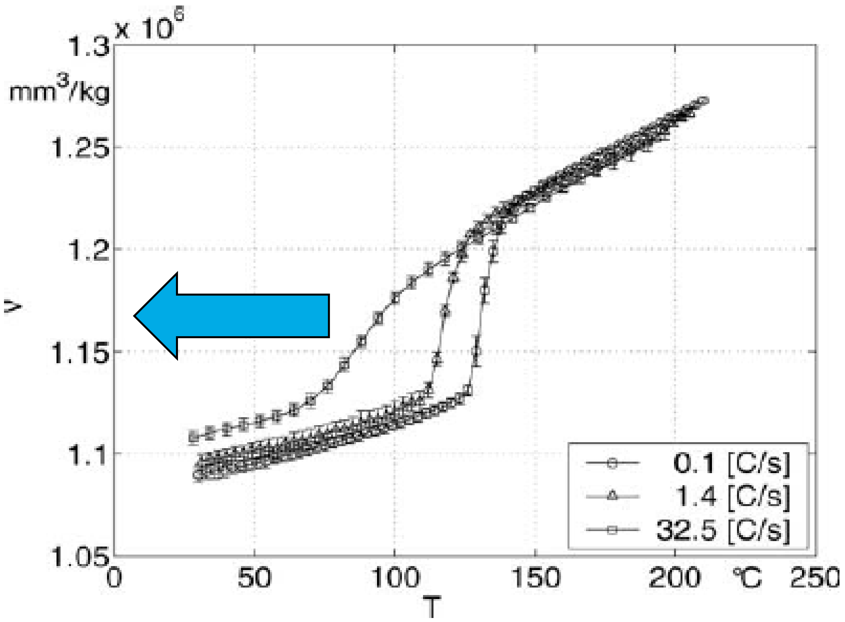


Fig. 9. Influence of cooling rate an the specific volume of i-PP at a pressure of 40 MPa. Average cooling rates during crystallization are given in the figure

van der Beek et. al. Inter. Polymer Processing, 20, 111-120, (2005).

Shear Rate Effect on Solidification

Measured Specific Volume during cooling after shearing

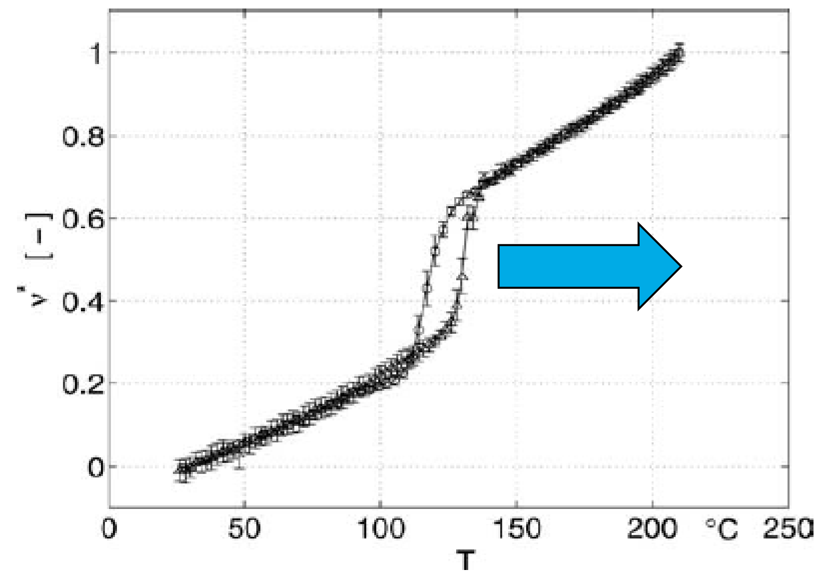


Fig. 10. Influence of shear flow an the normalized specific volume of i-PP. Shear is applied as a step function at 139 °C, with a shear rate of 38.5 1/s to a total shear of 117. Specific volume with (△) and without shear flow (○) is obtained at an average cooling rate during crystallization of 1.4 °C/s and a pressure of 40 MPa

Image: IME Technologies

van der Beek et. al. Inter. Polymer Processing, 20, 111-120, (2005).

Model of crystallization kinetics

$$G(T) = G_0 \exp\left[-\frac{U^*}{R(T - T_\infty)}\right] \exp\left[-\frac{f\,K_g}{T(T_m^0 - T)}\right],$$

$$T_\infty = T_g - 30, \quad f = \frac{(T + T_m^0)}{2T}$$

$$N = N_0 + N_f$$

$$\ln N_0 = a_N (T_m^0 - T) + b_N$$

$$\dot{N}_f + \frac{1}{\lambda_N} N_f = f(\Delta F_f, T)$$

G(T)

(Growth Rate)

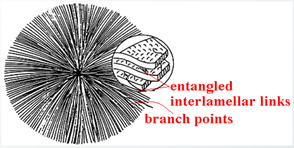
N(T, ΔF$_f$)

(Nuclei number density)

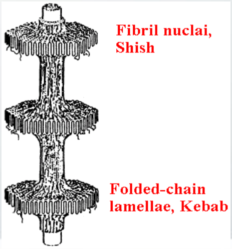
a_N, b_N, T^0_m, G_0 & K_g Are determined from DSC Experiments for each material grade

Hadinata et al. PPS 23

$$\phi = \frac{4\pi}{3} \int_0^t \dot{N}_0(s) \left[\int_s^t G(u)\,du\right]^3 ds$$



$$\psi = \pi \int_0^t \dot{L}_{total}(s) \left[\int_s^t G(u)\,du\right]^2 ds$$



$$\alpha = 1 - \exp\left[-(\phi + \psi)\right]$$

Crystallization Effect on Flow

- Calculate relative crystallinity (α) due to flow induced nucleation and temperature:

Viscosity

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

Specific Heat

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

Thermal Conductivity

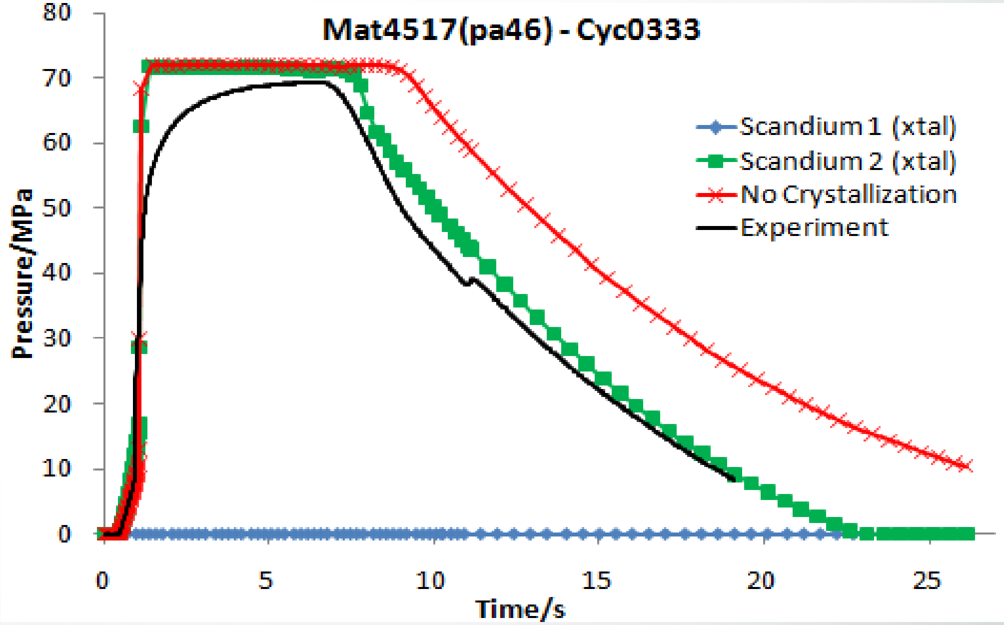
$$k(T)=\alpha k_s(T)+(1-\alpha)k_a(T)$$

Density

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

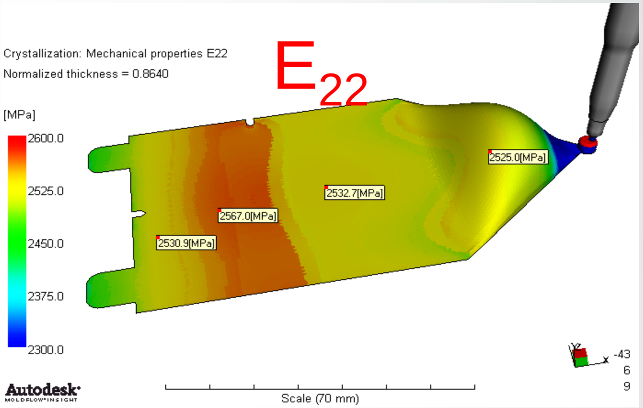
Temperature

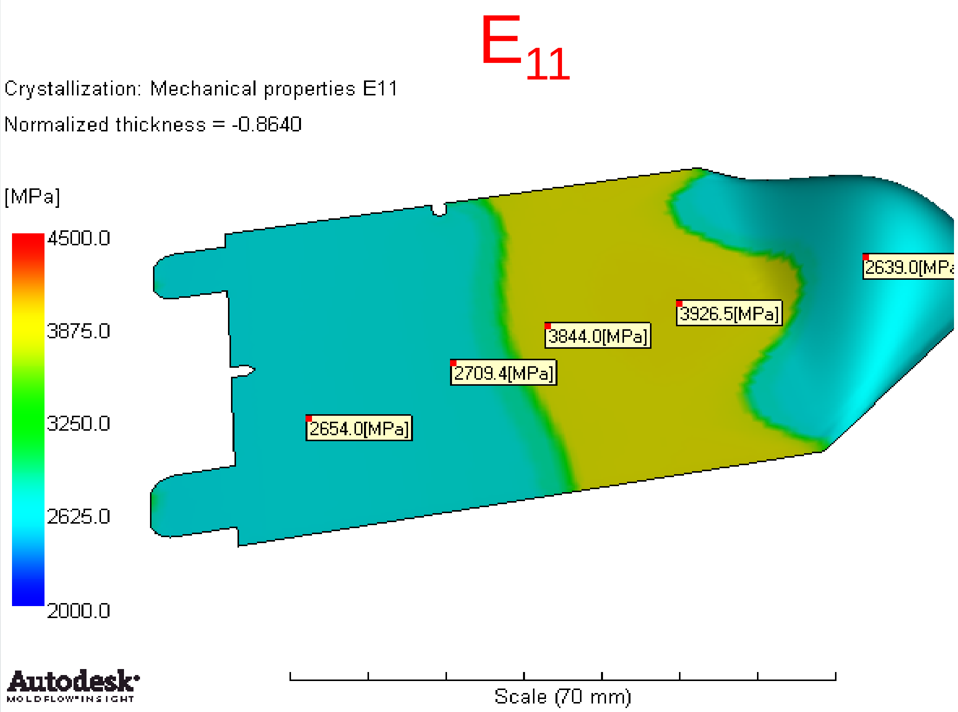
$$\rho(\alpha)\,c_p(\alpha)\frac{DT}{Dt}=k(\alpha)\nabla^2T+\boldsymbol{\sigma}:\mathbf{D}+\rho_c H_c\chi_\infty\frac{\partial\alpha}{\partial t}-\frac{T}{\rho(\alpha)}\frac{\partial\rho(\alpha)}{\partial T}\frac{Dp}{Dt}$$

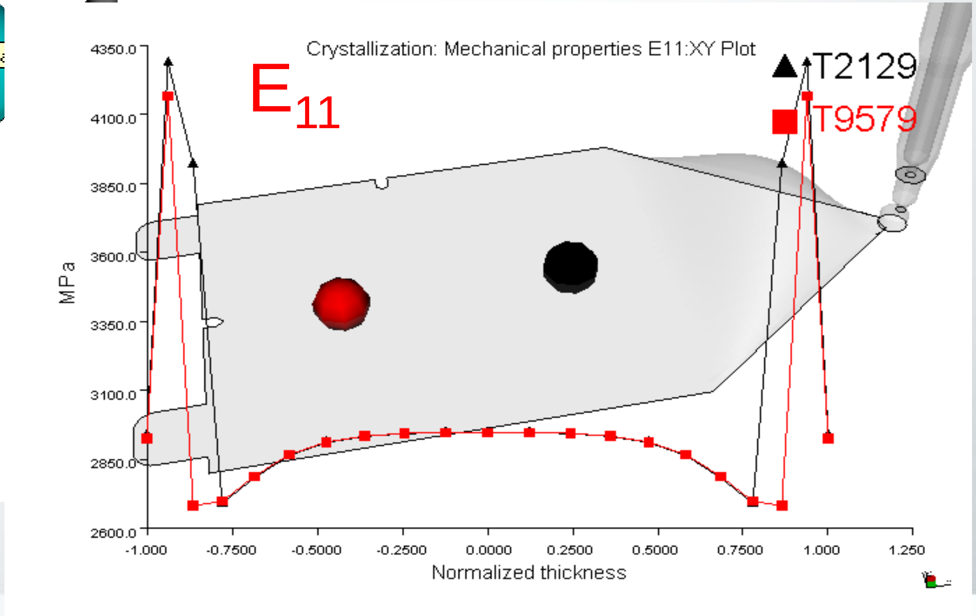


Predicted Modulus, E_{11} & E_{22}

- Varies through thickness
- Resolved in flow direction







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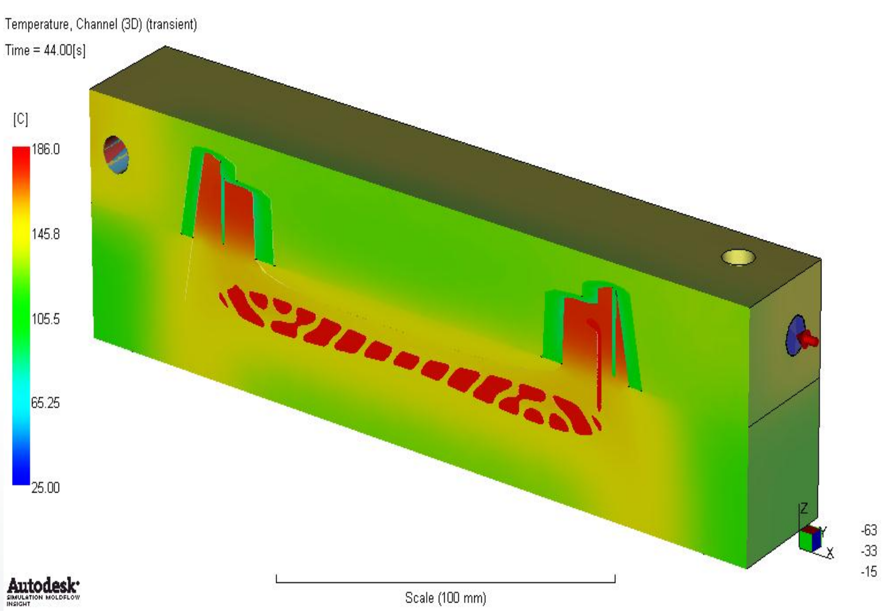


Viscoelastic Warpage

Stresses arise from mechanical and thermal strains according to the a viscoelastic stiffness tensor

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

Residual Stress

Stiffness tensor

Mechanical Strains

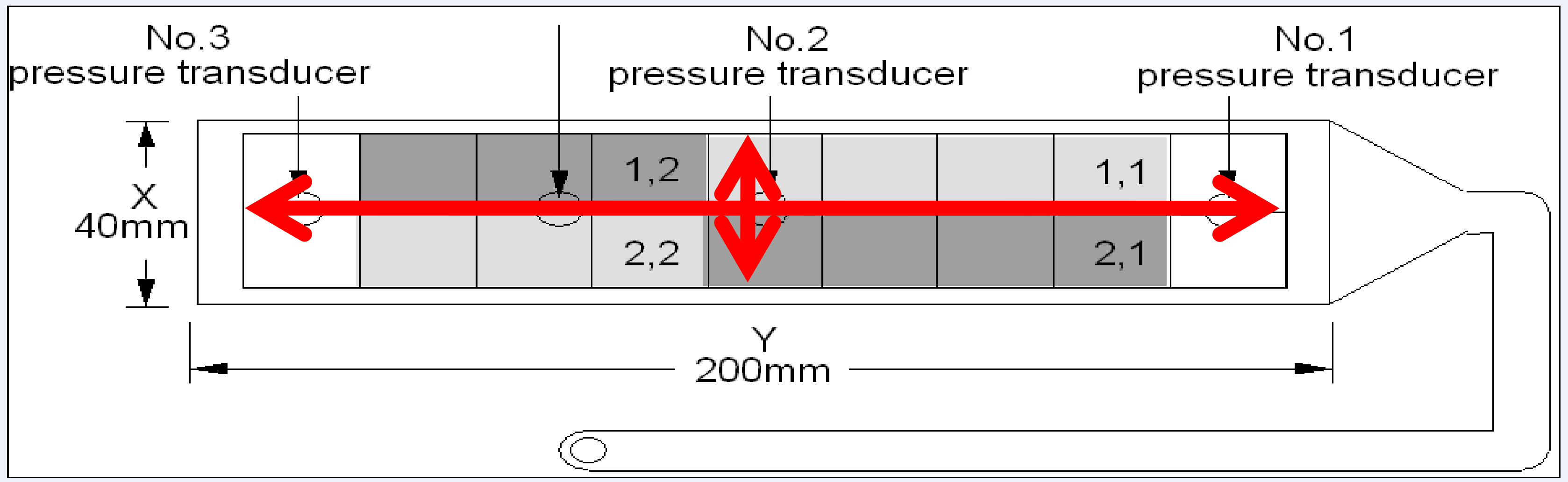
Thermal Strains

The stiffness tensor changes according to time and temperature

$$F(t) = \sum_{k=1}^{N} g_k \exp\left(-\frac{t}{\lambda_k}\right)$$

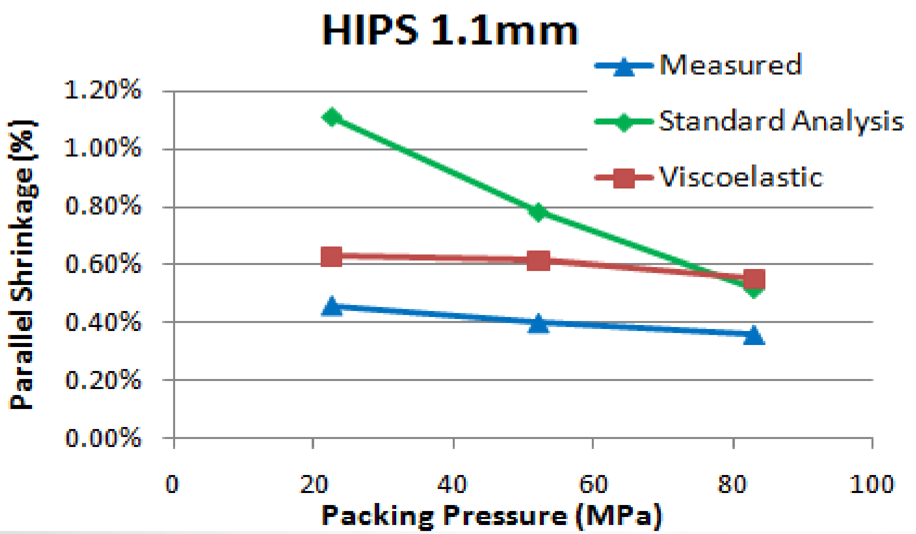
Viscoelastic Warpage for MP and DD

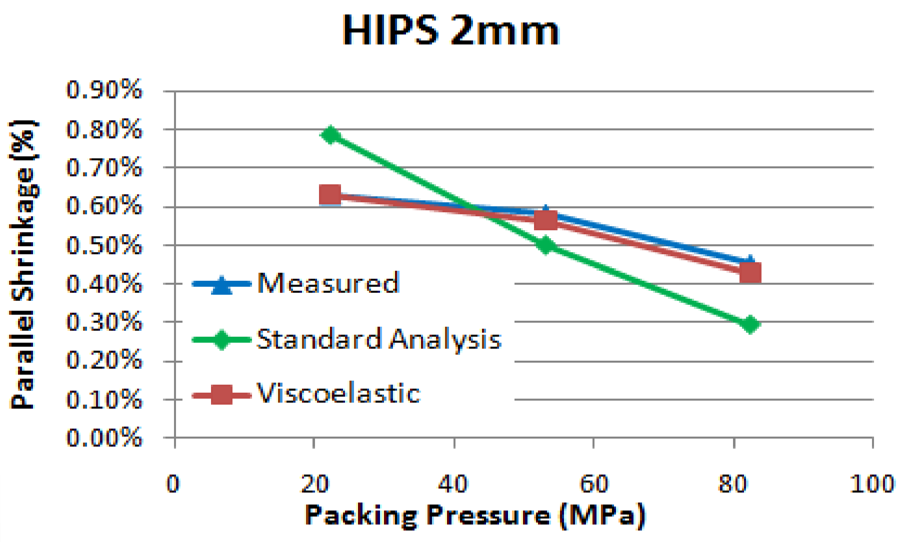
- Implemented in Midplane and Dual-Domain in Scandium Technology Preview
- Requires viscoelastic material data to be measured
- Viscoelastic simulation gives more realistic process sensitivity to packing pressure and packing/cooling time variation
- Validate using Shrinkage molding data



Viscoelastic Warpage on Tagdie Moldings

Examine trend with respect to Packing Pressure variation





Uncorrected (no CRIMS) shrinkage in the flow direction for an Amorphous non-fiber material. (HIPS)

Perpendicular Shrinkage shows a similar trend.

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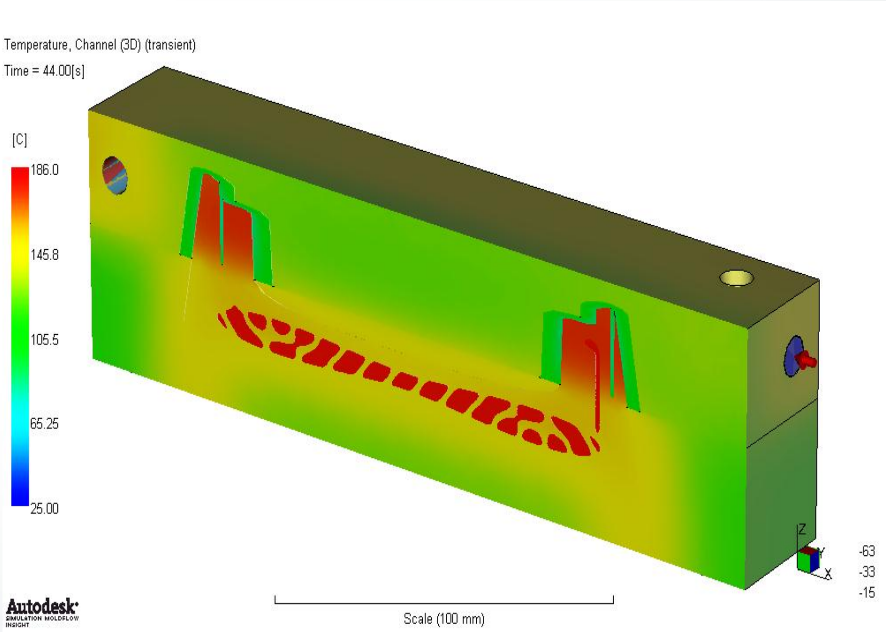
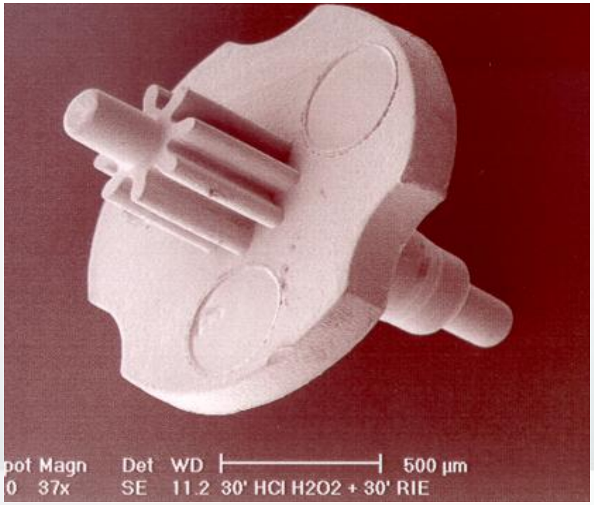


Micro Moulding Validation Challenges

- Conventional sensors are large in comparison to the part
- High speed of the moulding process
- Non-conventional injection moulding machines & mechanisms
- Emergence of additional physical phenomena
  - ⇒ Scale effects emerging at micro scale
    - Wall-slip ?
    - Changed heat transfer coefficient between polymer and mould
    - Surface tension ?



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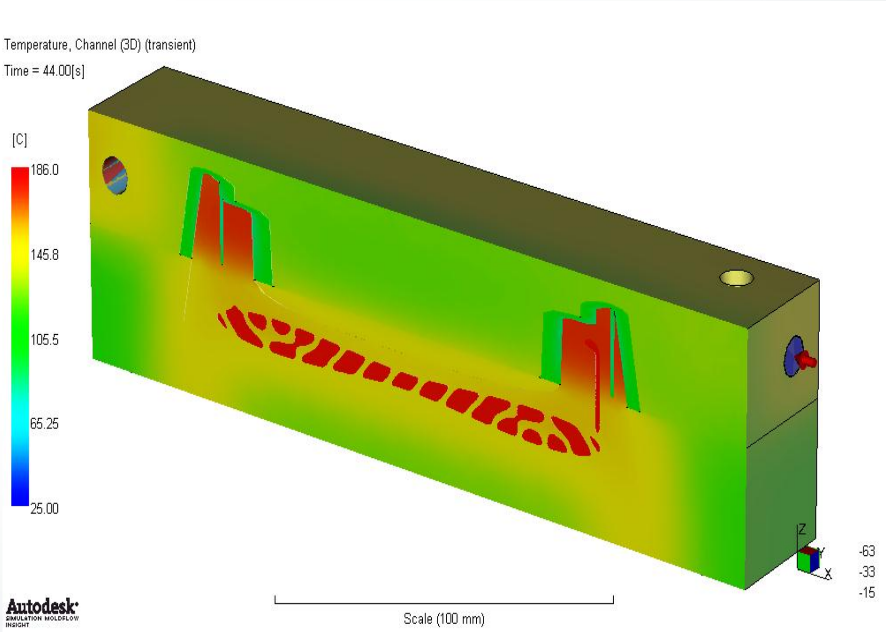
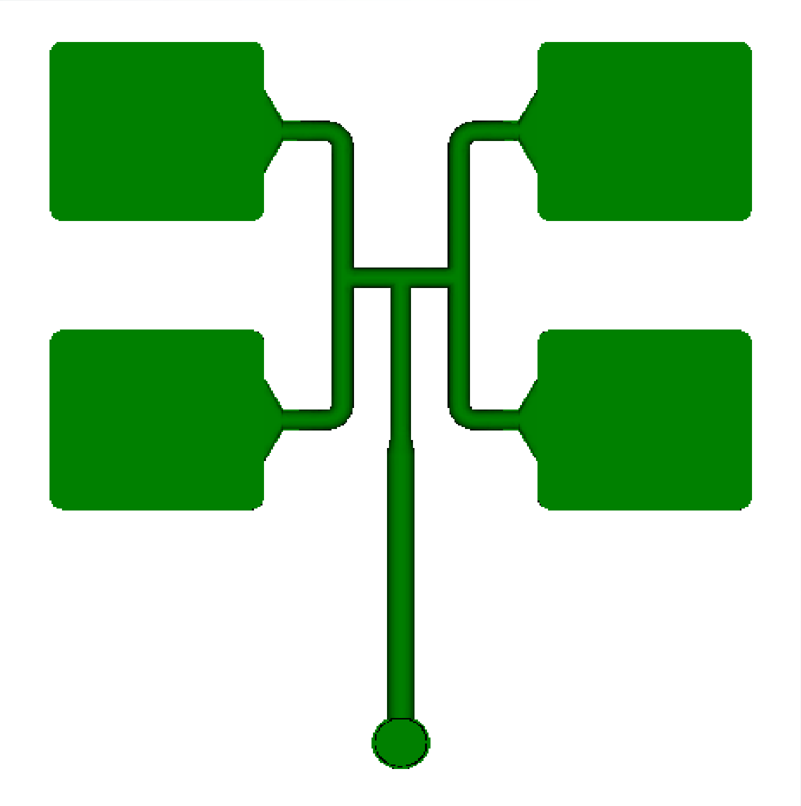
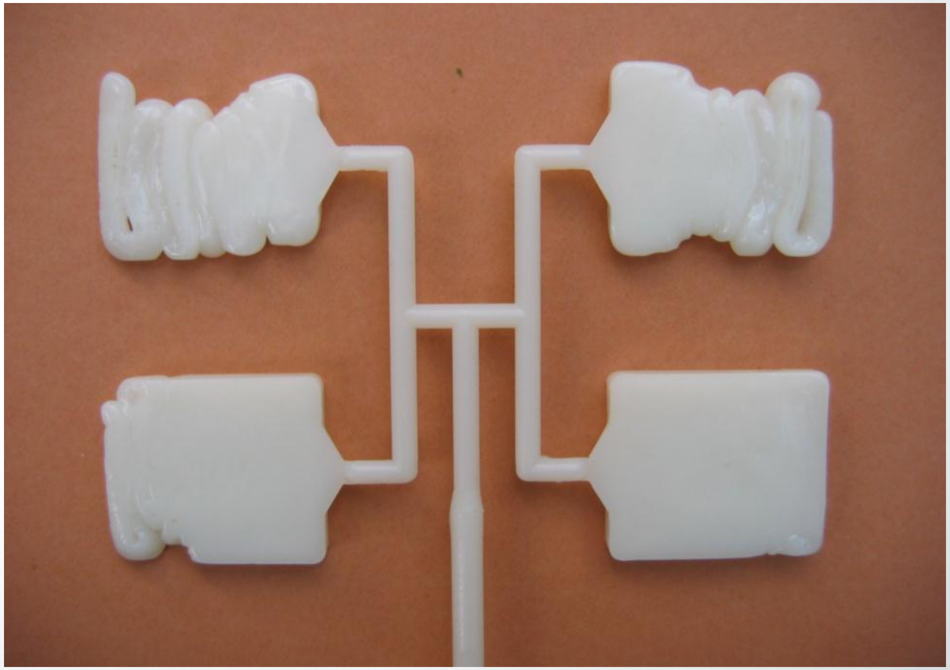


Runner imbalance: Test mold

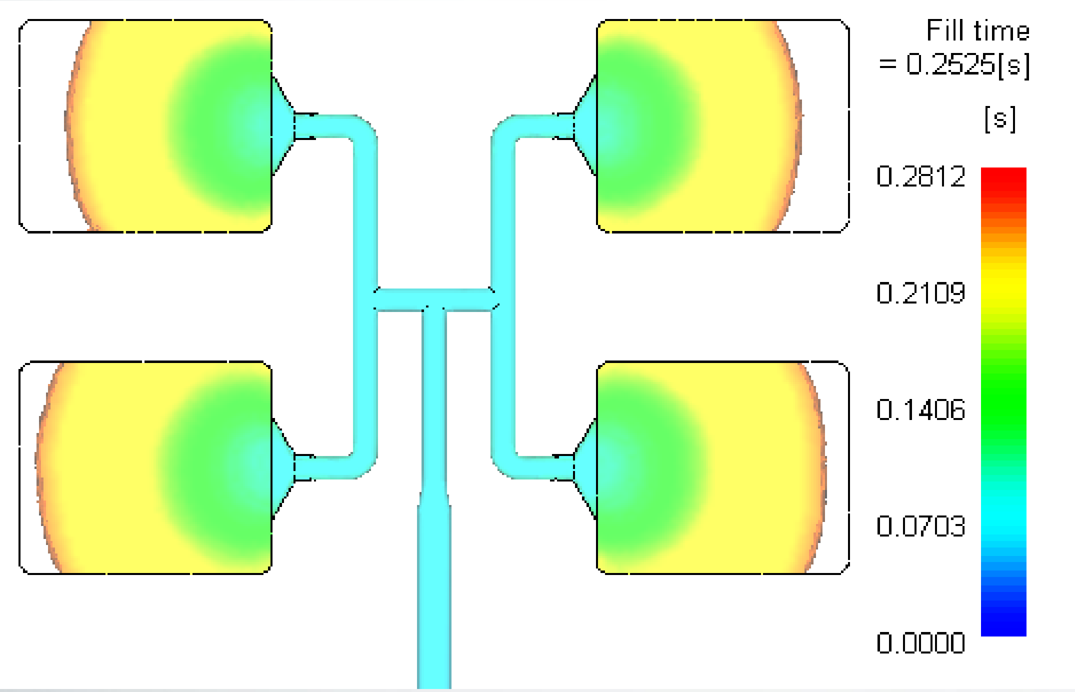
- Often observe imbalance in symmetric part
- Due to shear heating - convection pattern

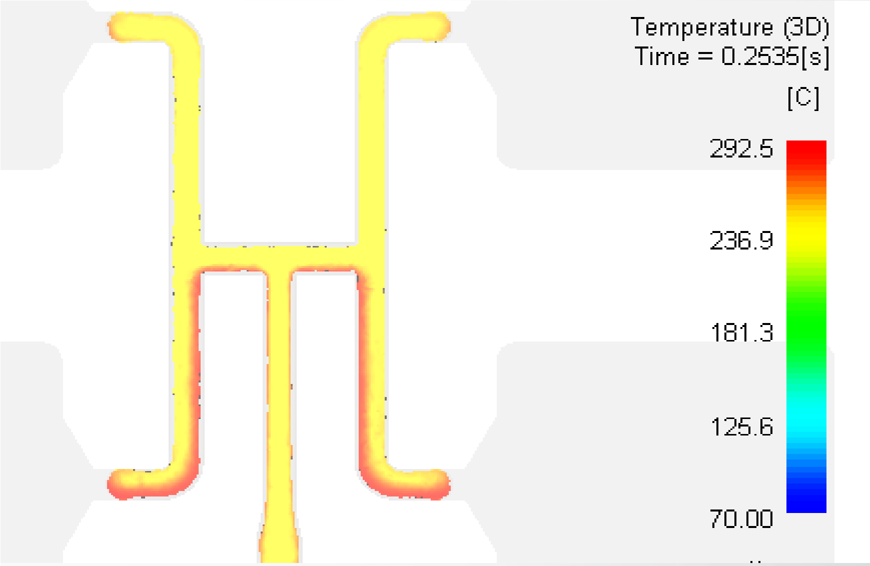




Runner imbalance: Fast injection

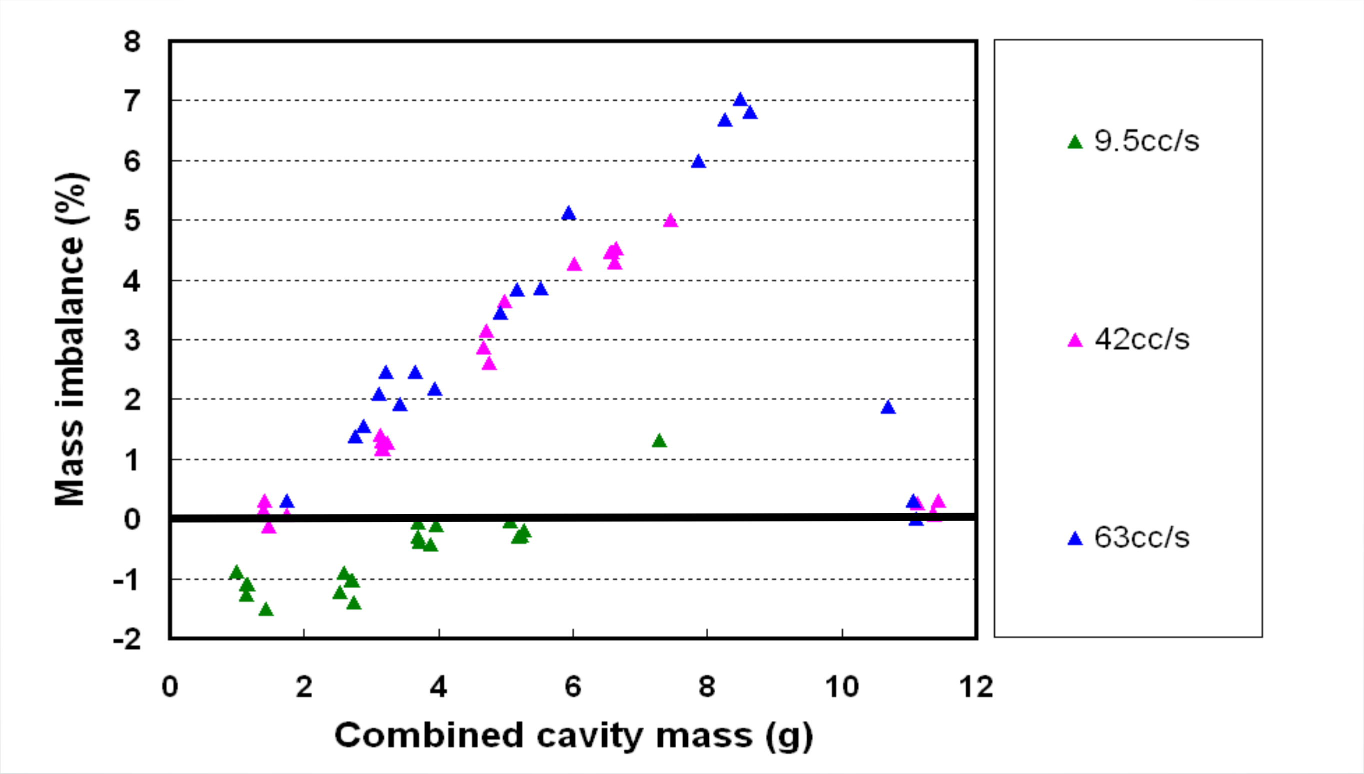
- Often observe imbalance in symmetric part
- Due to shear heating - convection pattern





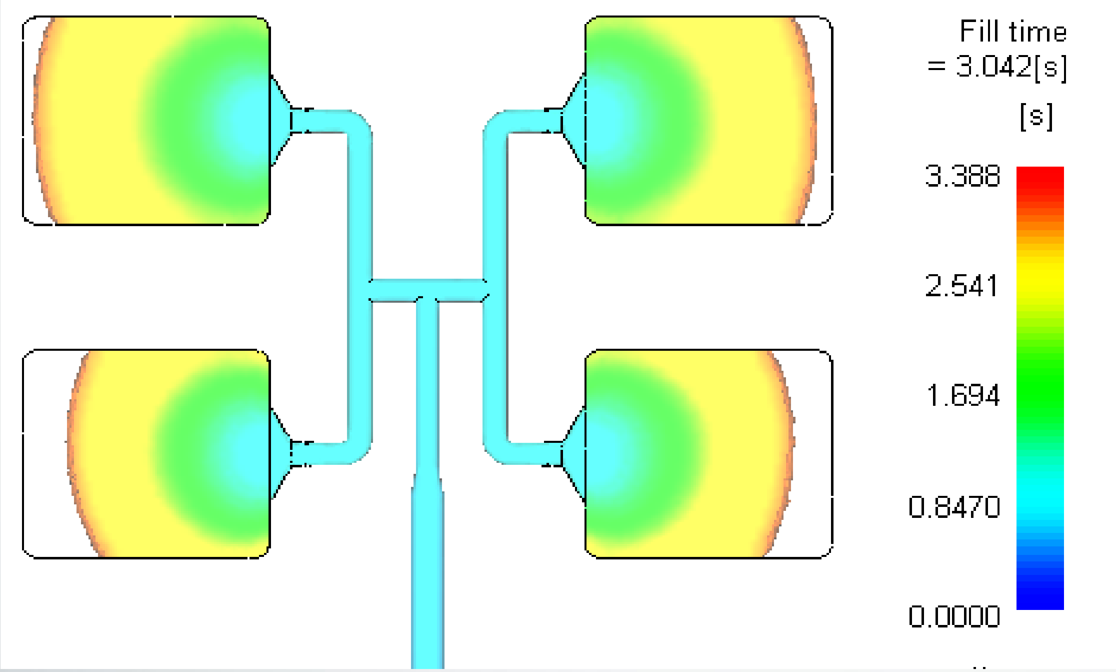
Runner imbalance: Short shot weights

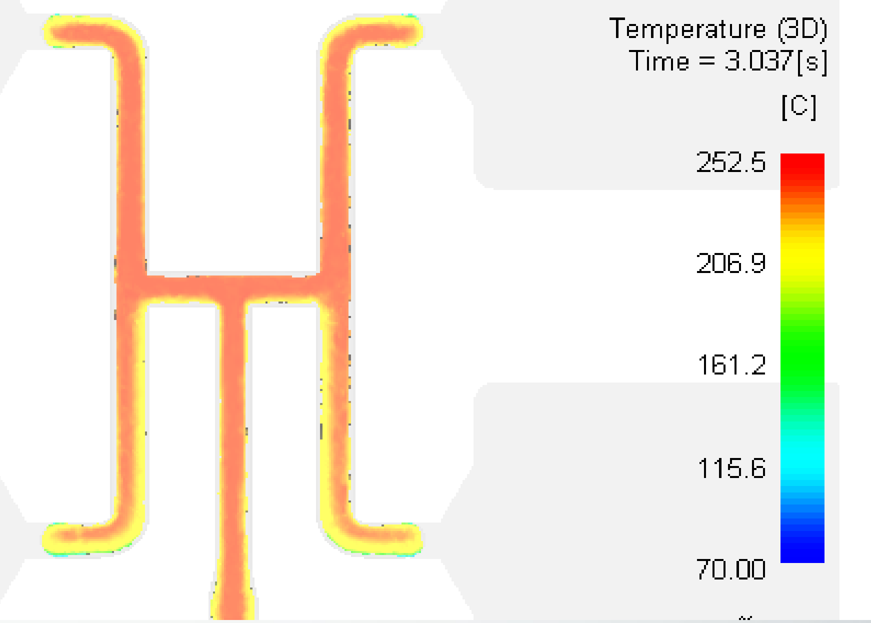
- Shear imbalance depends on injection rate
- Slower injection rates results in opposite imbalance due to cooling effect



Runner imbalance: Slow injection

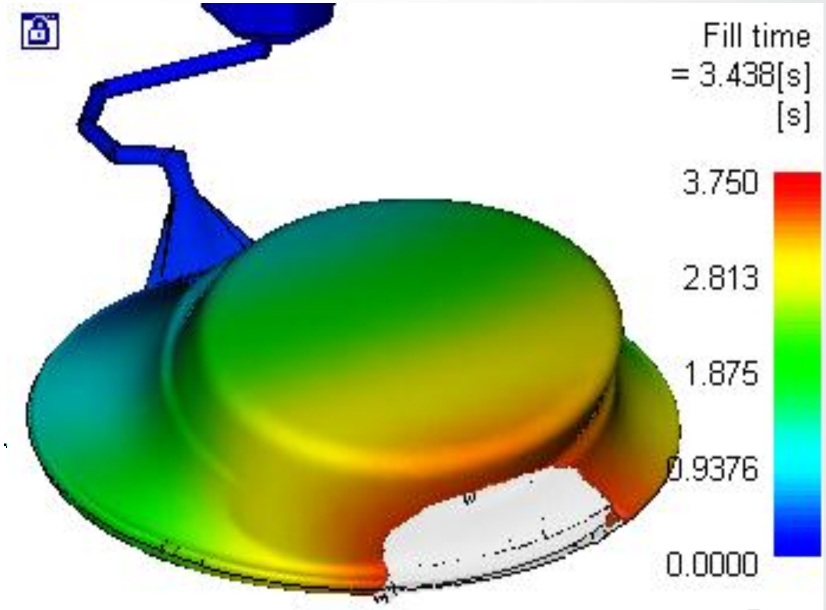
- Slow injection rate

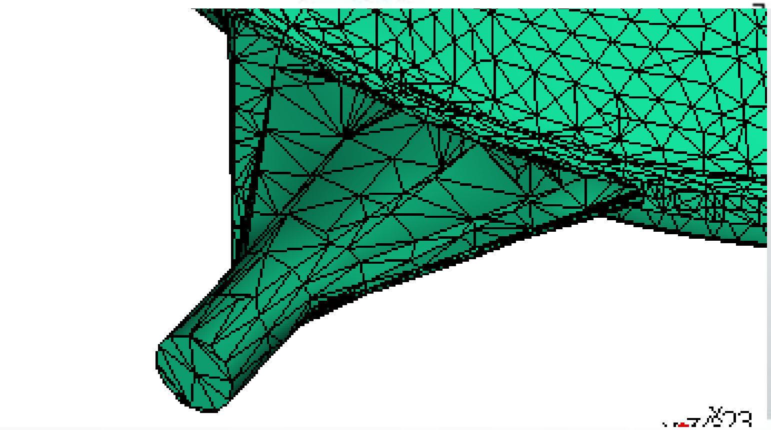




Edge flow in PC lens: Fill pattern

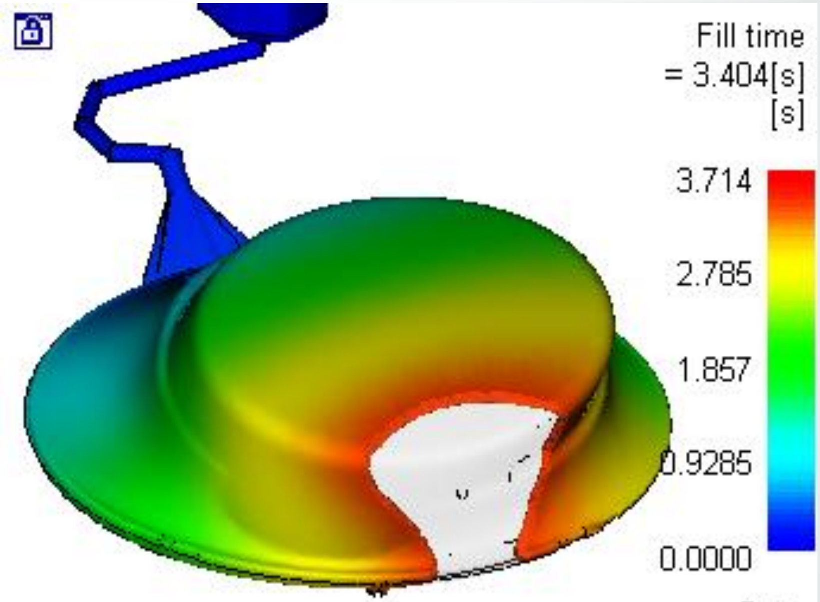
- Initial analysis does not agree with molding short shot

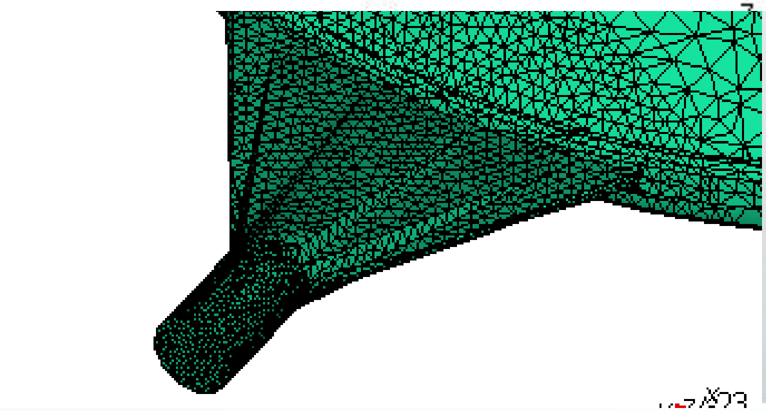




Edge flow in PC lens: Fill pattern (2)

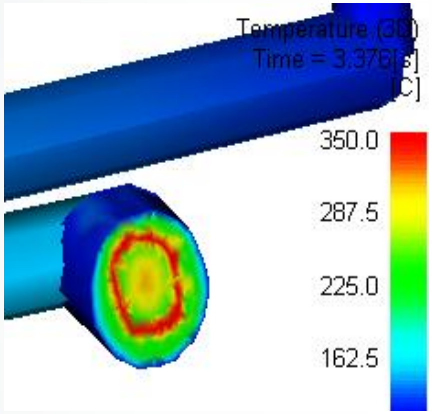
- Refined gate at mesh gives better agreement

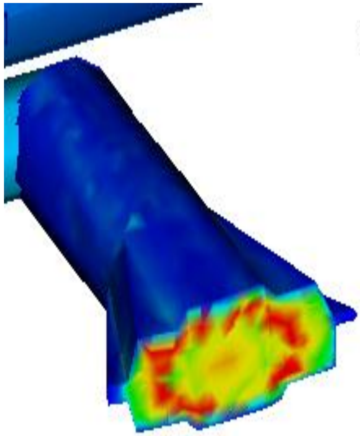


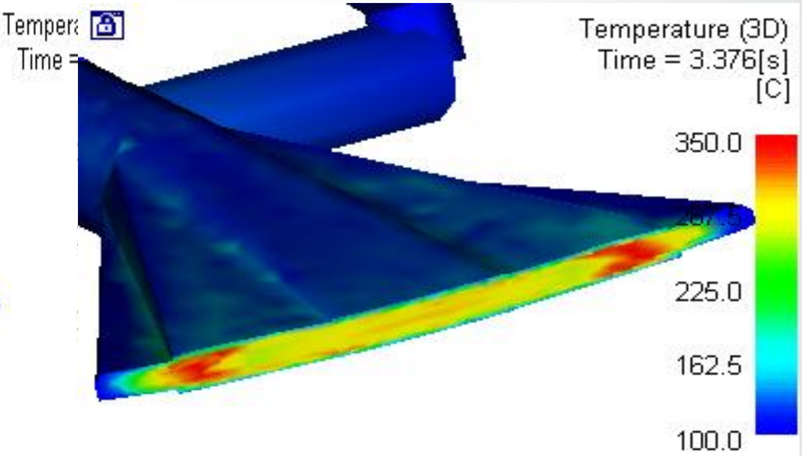


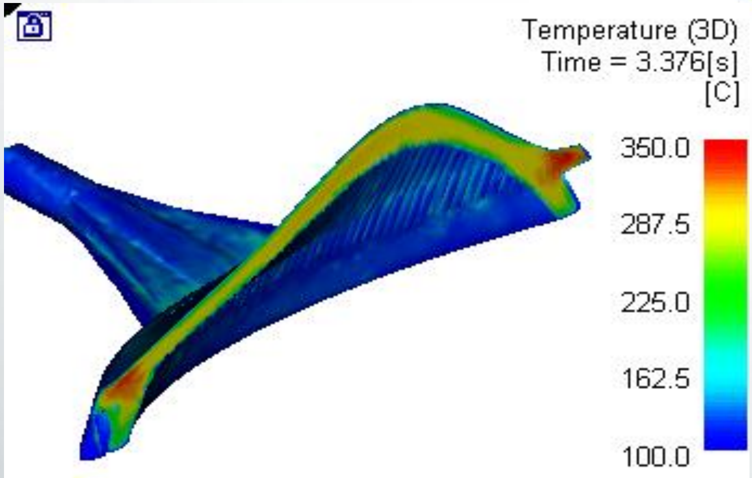
Edge flow in PC lens: Temperature slice

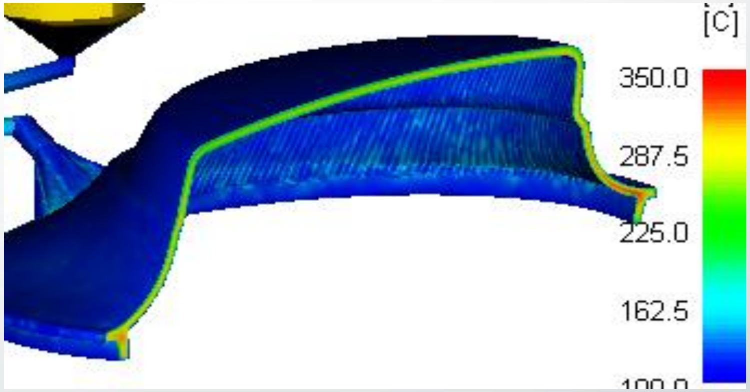
- Temperature distribution in the runner and gate











Ear-flow in fiber filled materials

- Akay & Barkley*
  - Increasing the fiber content caused advanced flow at the edge
  - Maranyl A690 (PA)
  - Possibly due to fiber alignment and effect on viscosity

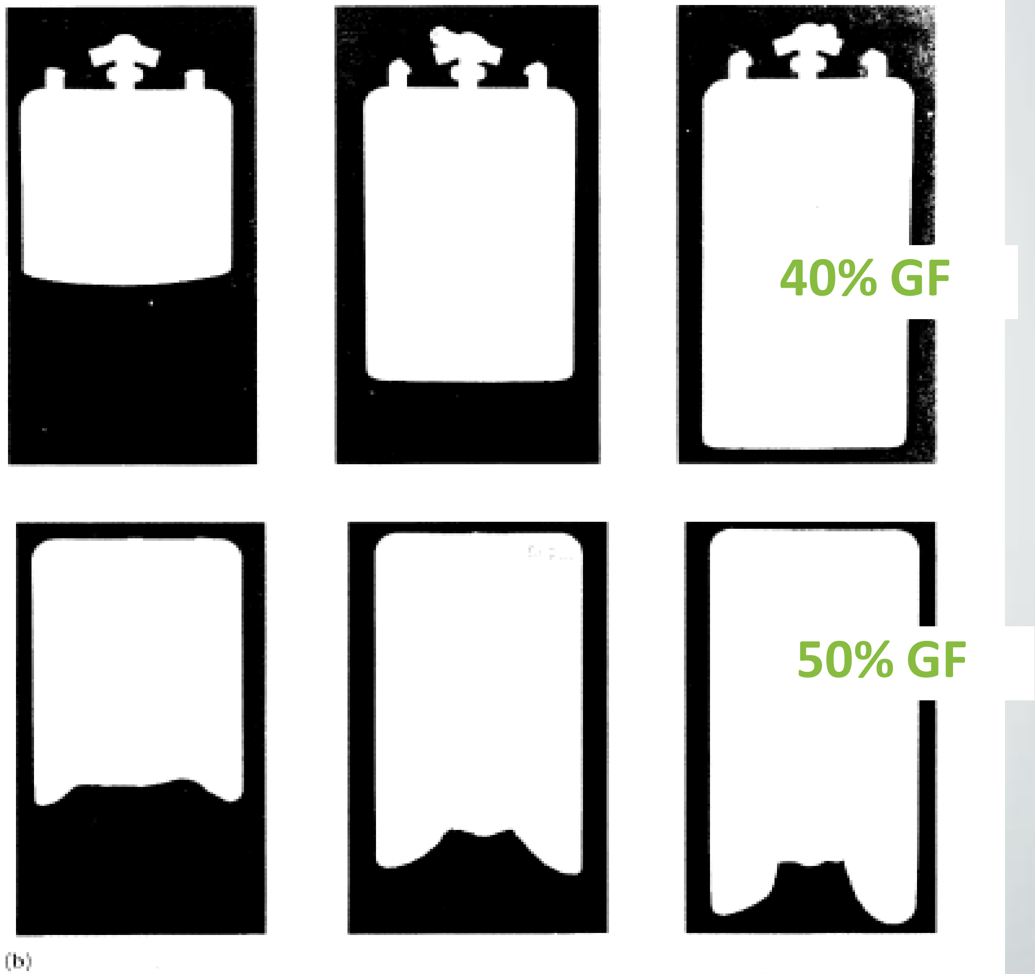


Fig. 6 Short-shot mouldings typical of (a) SFRPA30 and SFRPA40; (b) SFRPA50.

*Plastics, Rubber and Composites Processing and Applications Vol 20 (3), 1993. pp137-149

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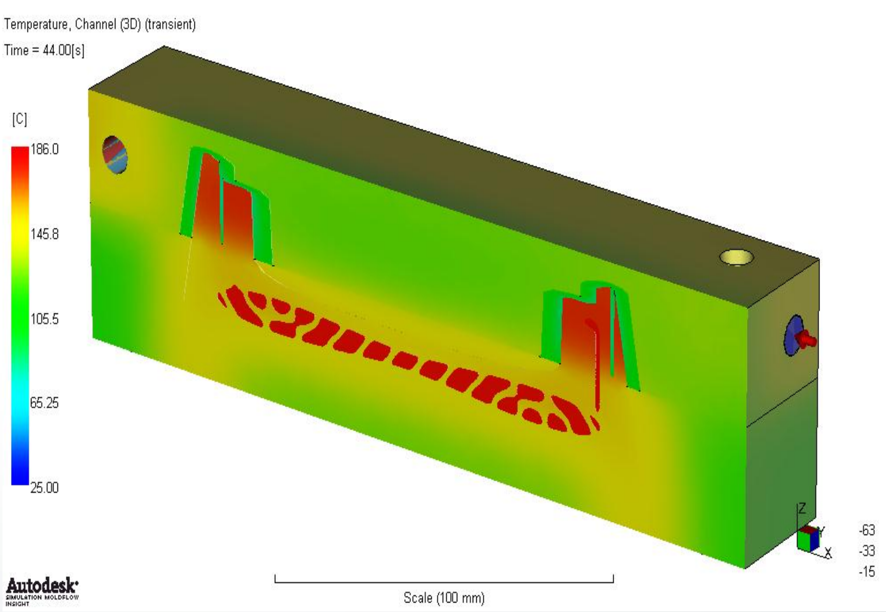
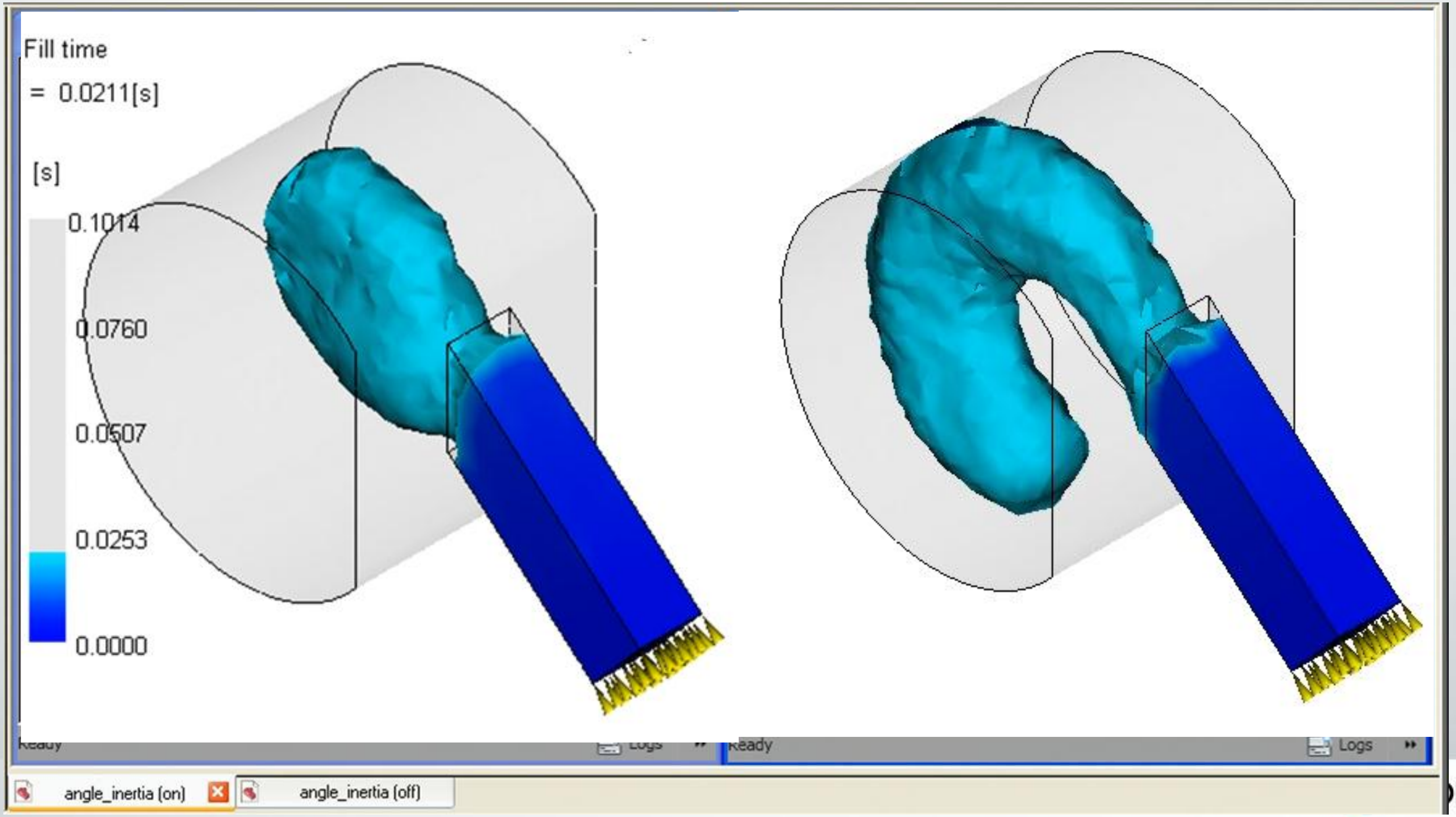


Wall-Slip for 3D Flow

No Slip

With Slip



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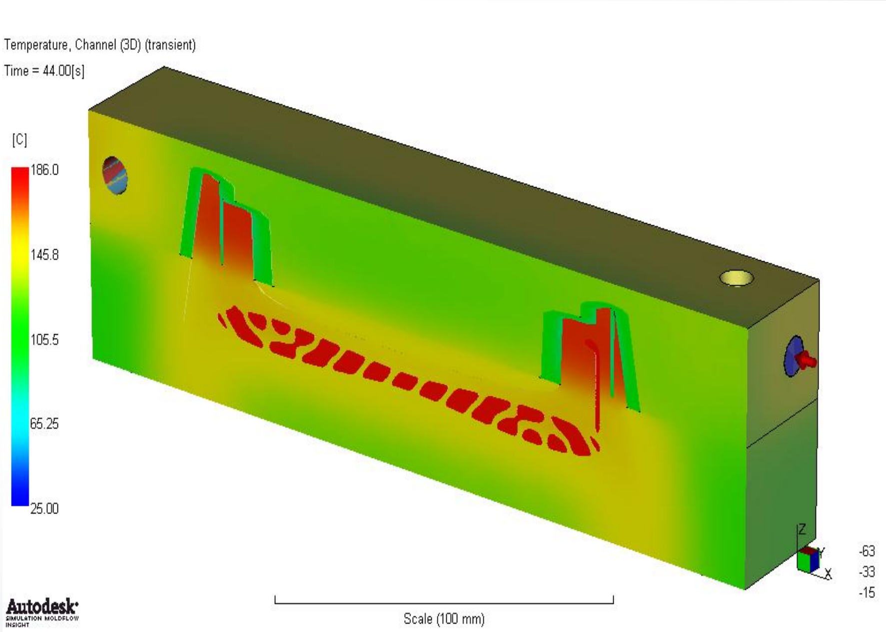

Tiger Stripes

- Caused by a viscoelastic flow instability?