A Modular Simulation Approach for Predicting Molding and Process-Induced Deformations (PID) for Glass Mat Thermoplastics (GMT)

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1. Introduction & motivation
2. Molding simulation
3. Warpage simulation
4. Conclusion & outlook
1. Introduction & motivation

Manufacturing technology and material

- Molding of GMT materials can be divided into the stages thermoforming and squeeze flow

- Investigated material: Tepex flowcore (Lanxess)
  - Matrix: PA6 (engineering thermoplastic)
  - Fibers: Glass mat
    - Random fiber orientation
    - High fiber volume content (47 vol.%)
    - High fiber length (30 – 50 mm)

- Major challenges:
  - Wrinkling and incomplete mold filling
  - Process-induced deformation / warpage

Schematic of the stages during GMT molding

Exemplary processing issues
Agenda

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2. Molding simulation

Challenge and approach for molding simulation

• Manufacturing process simulation is a powerful tool for the optimization of manufacturing processes

• **Challenge for molding simulation with GMT:** Existing numerical techniques are capable to predict either thermoforming or squeeze flow

➤ **Approach:**
Development of a sequential approach for molding simulation of GMT materials

<table>
<thead>
<tr>
<th></th>
<th>Stage 1: Thermoforming simulation</th>
<th>Stage 2: Squeeze flow simulation</th>
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<tbody>
<tr>
<td>Lagrangian</td>
<td>✔️</td>
<td>✗</td>
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<tr>
<td>Eulerian</td>
<td>✗</td>
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Schematic illustration of the challenges and approaches chosen for molding simulation with GMT.
2. Molding simulation

Workflow for sequential molding simulation

**Step 1:**
Thermoforming simulation
*Lagrangian*

- Deformed geometry
- Fiber orientation
- Temperature
- Crystallinity

**Step 2:**
Squeeze flow simulation
*Eulerian*

- ABAQUS + API
- MpCCI
- Autodesk Moldflow + API

**Major achievements:**
- Unified material modeling across the steps
- Mapping of relevant state variables
- Modularity through neutral exchange format
2. Molding simulation

Material modeling and parameterization

- **Cauchy stress** is evaluated separately for the molten and the solid material state
  
  \[ \sigma(X, T) = X\sigma_{\text{solid}} + (1 - X)\sigma_{\text{molten}}(T) \]

- **Molten material state**: Equation of state (EOS) and a nonlinear viscosity model
  
  \[ \sigma_{\text{molten}} = -pI + \sigma_{\text{visc}}(T, \dot{\gamma}) \]

- **EOS**: Tait-model (reformulated)
  
  \[ p = B \left\{ \exp \left( \frac{1}{C} (1 - J) \right) - 1 \right\} \]

- **Viscosity**: Cross-WLF model
  
  \[ \eta(T, \dot{\gamma}) = \frac{\eta_0 - \eta_\infty}{1 + \left( \frac{\eta_0}{\eta_\infty} \right)^{1-n}} + \eta_\infty \text{ with } \eta_0 = D_1 \exp \left( \frac{A_1(T - T_2)}{A_2 + T - T_2} \right) \]
2. Molding simulation

Application example: Geometry and process settings

- **Hat section geometry** is adopted to demonstrate the workflow

- **Key data manufacturing process**
  - Press cycle time: 8.9 s
  - Tool temperature: 150 °C *(top and bottom)*
  - Blank dimensions: 950 x 335 x 4 mm³
  - Blank temperature: 287.3 °C *(estimated temperature after transfer through 1D thermal analyses)*
2. Molding simulation

Application example: Thermoforming simulation (AB AQUS/Explicit + API)

- Beginning of thermoforming simulation - 0.0 s
- End of the gravity step - 6.0 s
- End of the thermoforming step - 8.0 s
- End of the thermoforming step (detail) - 8.0 s

Temperature range: 150.0°C to 290.0°C
2. Molding simulation

Application example: Thermoforming simulation (ABAQUS/CEL + API)

Intermediate during squeeze flow - 8.3 s

Intermediate during squeeze flow - 8.6 s

End of the squeeze flow step - 8.9 s
Agenda

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3. Warpage simulation

Analysis of Process-Induced Deformations (PID) and viscoelasticity

- PID / warpage is induced by thermal strains during solidification and cooling:
  - Thermal expansion
  - Shrinkage

- Solidification and cooling can be divided into different stages:
  1. Fully molten \((t = 0)\)
  2. Solidification in closed mold \((t < t_{\text{demold}})\)
  3. Demolding \((t = t_{\text{demold}})\)
  4. Relaxation of residual stresses \((t > t_{\text{demold}})\)

➢ Viscoelasticity plays a major during solidification and cooling
3. Warpage simulation

Material modeling and parameterization

**Thermal strains**

- Thermal strain increment splits into thermal expansion and shrinkage due to crystallization:
  \[
  \Delta \varepsilon_{th} = \frac{\Delta \varepsilon_{exp} \beta + \Delta X \alpha}{\Delta \varepsilon_{sh}}
  \]
- Parameterization thermal strains upon pvT data

**Viscoelasticity**

- Mechanical modeling is based on Prony and time temperature superposition (TTS)
  \[
  C(t) = C_0 \left( 1 - \sum_{p=1}^{N} g_p \left( 1 - \exp\left(-\frac{t}{\tau_p}\right) \right) \right)
  \]
- Parameterization TTS upon DMA test results and Prony series upon master curve

Tait EOS for flowcore for parameterization of thermal strains

Flowcore master curve at 45 °C determined through TTS
3. Warpage simulation

Prediction of local material properties through homogenization

• Manufacturing process induces a change in fiber orientation due to material flow

• Local fiber orientation is predicted in molding simulation through Jefferey’s equation:

\[
\frac{\partial N}{\partial t} = \omega \cdot N - N \cdot \omega + \lambda (D \cdot N + N \cdot D + 2N : N)
\]

• Effective local material properties of the composite are homogenized with Mori-Tanaka’s equation:

\[
\bar{C}_{MT} = C_{M} + c_{M} \left\langle (C_{F} - C_{M}) A_{F0}^{SIP} \right\rangle_{F} A_{M}^{MT}
\]

• Hypothesis for viscoelasticity:
  • Only module \( C_{0} \) is influenced by local orientation
  • Retardation times are orientation independent
3. Warpage simulation

Application example (ABAQUS + API)

Process-induced deformation / warpage

Relative crystallinity

Temperature
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4. Conclusion & outlook

Conclusion

• A modular virtual process chain for GMT materials is implemented
  • Sequential molding simulation
  • Warpage simulation under manufacturing effects

• The approach is successfully applied to a hat section geometry for demonstration
  • Thermomechanical molding simulation is required due to significant cooling
  • Viscoelasticity plays a major role during solidification and cooling

Outlook

• Molding simulation: Anisotropic viscosity

• Warpage simulation: Comparison viscoelastic approach to simplified material modeling:
  • Path-dependent approach
  • CHILE approach

• Validation of the proposed virtual process chain through correlation with experimental tests
  • Short shots
  • Local μCT scans
  • Surface scans

• Industrialization of the proposed approach through the spin-off company SIMUTENCE
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