SPE ACCE 2020

A Coupled Thermomechanical Simulation Approach for Thermoforming of Glass Mat Thermoplastics

D. Dörr, C. Xu, R. Gergely, S. Ivanov, F. Henning, and A. Hrymak

July 3, 2020

A cooperation between:

Western Engineering

GM RESEARCH & DEVELOPMENT

KIT Karlsruhe Institute of Technology

FAST Institut für Fahrzeugsystemtechnik

Fraunhofer ICT

Outline

1. Introduction & motivation
2. Characterization results
3. Material modeling & parameterization
4. Thermoforming simulation results
5. Conclusion & outlook

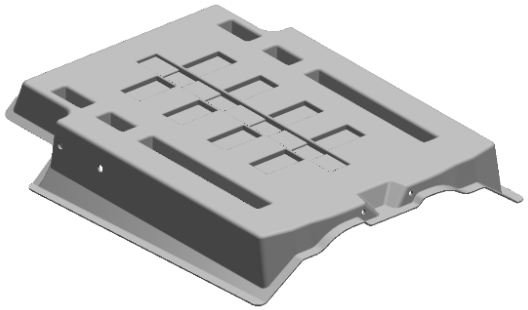
1. Introduction & motivation

- **Chopped fiber composites** reveal the potential to be shaped into complex geometries

- 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)

- Processing is determined by **initial mold coverage**
  - Low mold coverage → compression molding
  - High mold coverage → thermoforming

CAD data nominal part



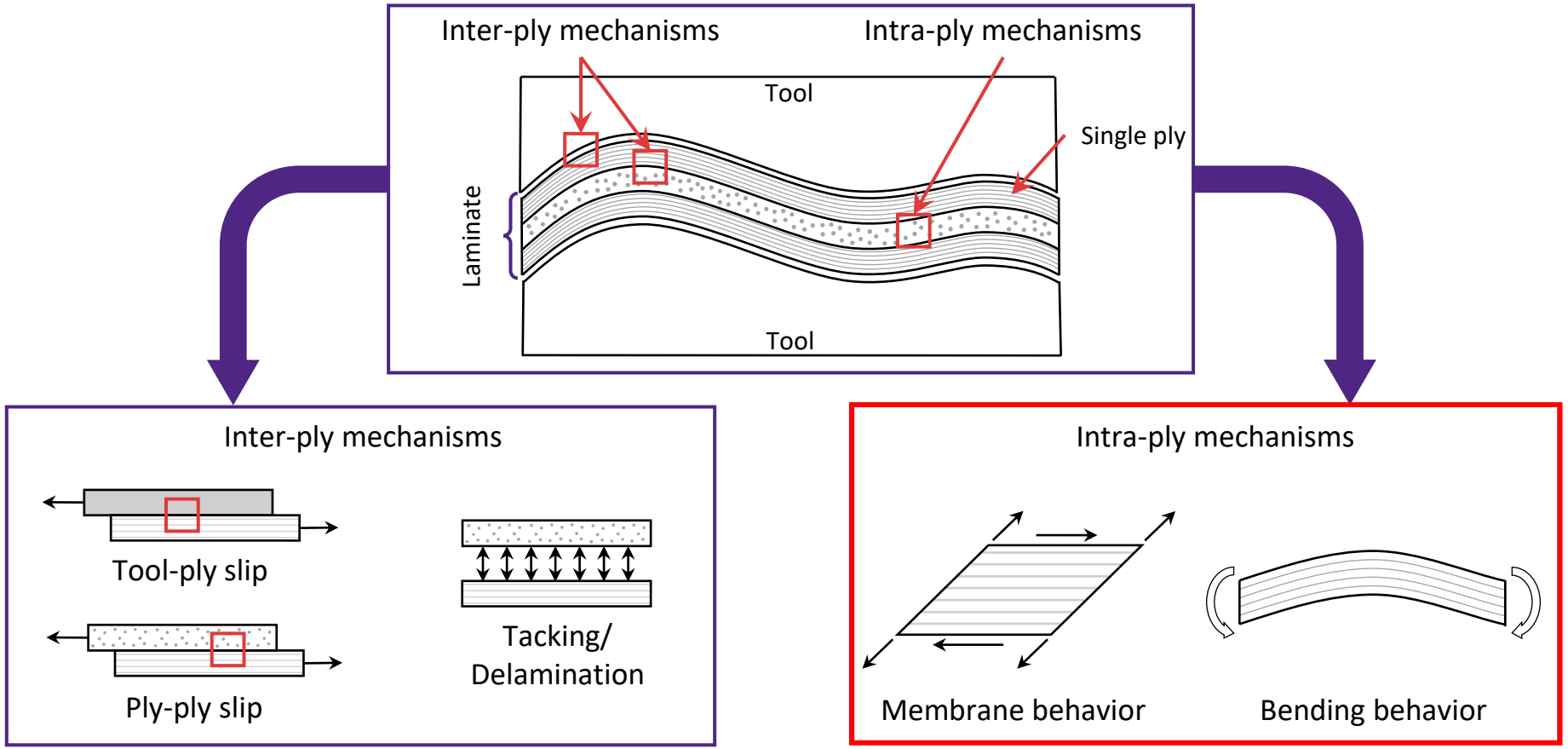
Surface scan

Exemplary processing result with Tepex flowcore for a high mold coverage at a remaining tool travel of 5 mm

➢ **Application of thermoforming characterization and simulation approaches to Tepex flowcore**

2. Characterization results

Deformation mechanisms during thermoforming



2. Characterization results

Characterization approaches

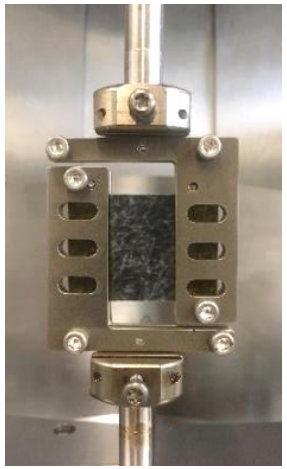
- Existing material characterization techniques originally developed for thermoplastic UD-tapes are adopted

➢ Rheometer tests with customized setups to capture temperature- and rate-dependent material behavior

- Characterized deformation mechanisms:
  - Membrane behavior → Torsion-bar test [1]
  - Bending behavior → Rheometer bending test [2]

- Varied parameters:
  - Deformation rate
  - Temperature
  - Specimen thickness (only for torsion bar test)

Anton Paar MCR501 rheometer



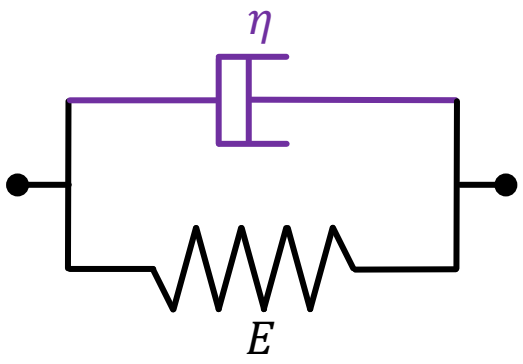
Rheometer bending test

Torsion-bar test

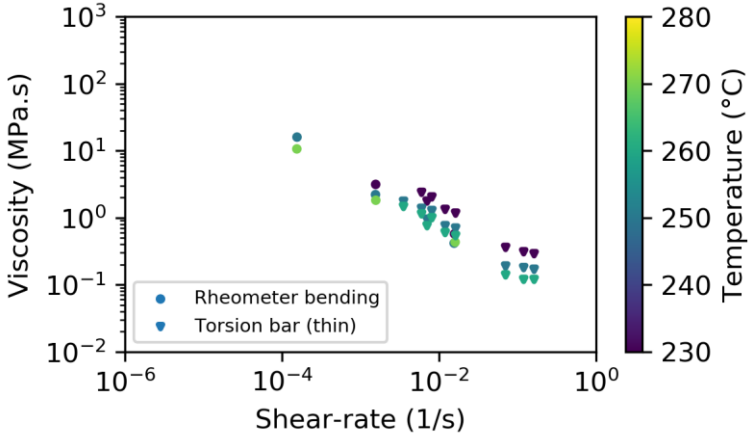
2. Characterization results

Extraction of viscosity and elastic modulus

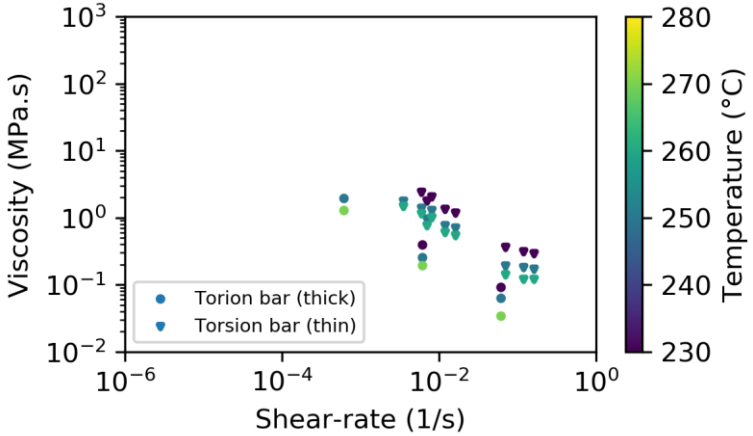
- Voigt-Kelvin approach defines a constant viscosity η and an elastic modulus E for each testing condition



- Observations for the **viscosity** η
  - High sensitivity to temperature and shear-rate
  - High correlation between torsion bar tests (thin) and rheometer bending tests
  - Lower viscosity values for torsion bar tests (thick)



Results from rheometer bending and torsion bar test (thin)

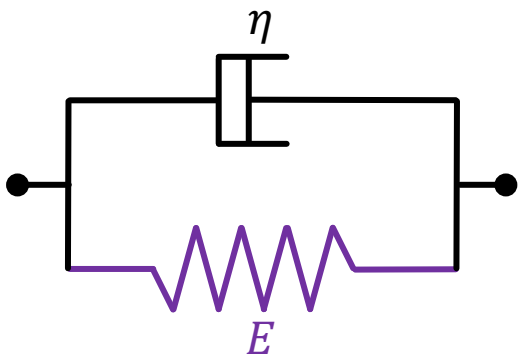


Results from thick and thin torsion bar test

2. Characterization results

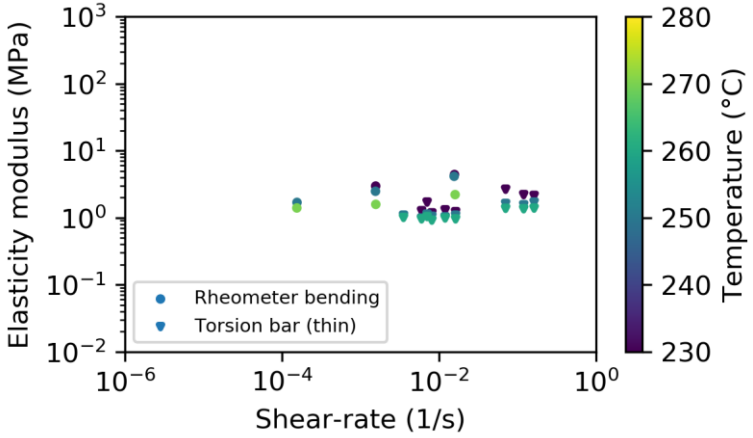
Extraction of viscosity and elastic modulus

- Voigt-Kelvin approach defines a constant viscosity η and an elastic modulus E for each testing condition

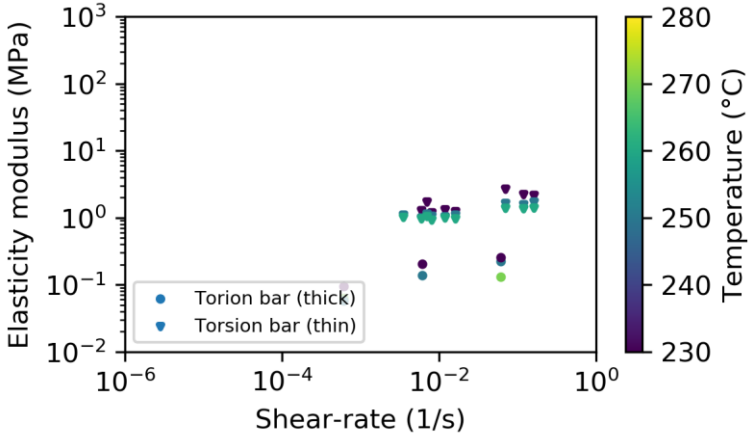


- Observations for the **elastic modulus** E
  - Overall low elasticity modulus (< 10 MPa)
  - High correlation between rheometer bending and torsion bar tests (thin)
  - Lower elastic moduli for torsion bar tests (thick)

➢ **Results from thin torsion bar (thin) and rheometer bending tests will be adopted for parameterization**



Results from rheometer bending and torsion bar test (thin)



Results from thick and thin torsion bar test

3. Material modeling & parameterization

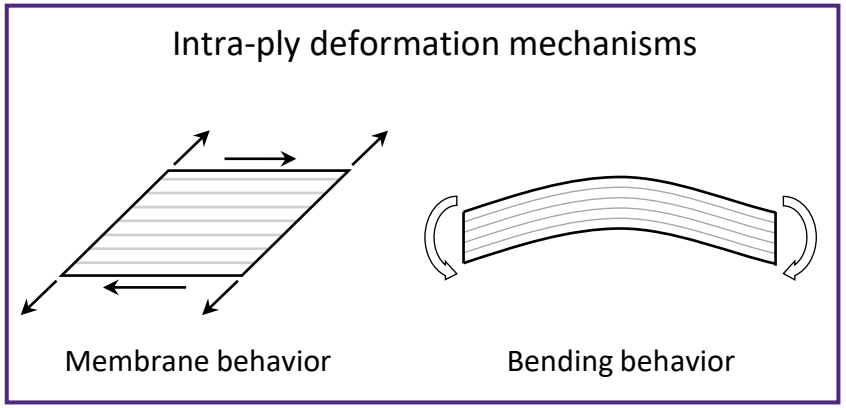
Decoupling of membrane and bending behavior

- **ABAQUS/Explicit** in combination with several user-subroutines is applied for thermomechanical analysis

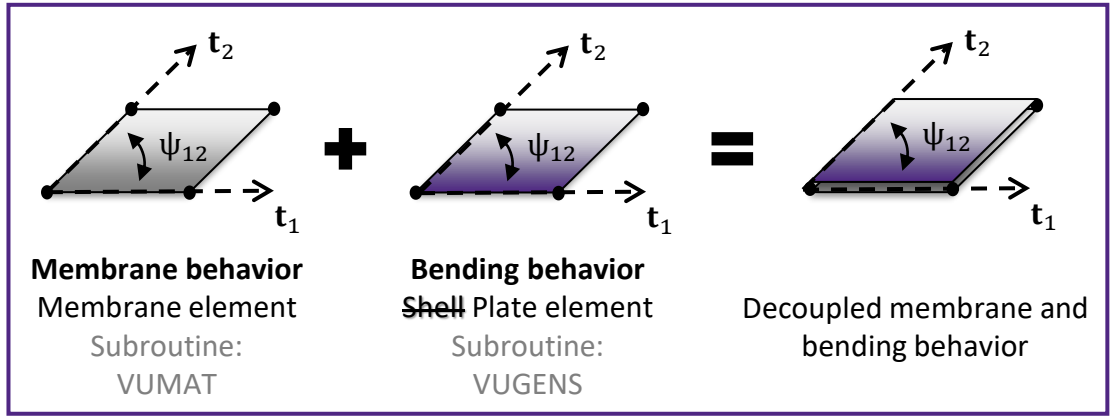
- Basic approach originating from thermoforming simulation of thermoplastic tapes [3,4,5]

- Material characteristics thermoplastic tapes at processing conditions:
  - High fiber stiffness
  - Low bending stiffness
  - ➢ Conventional shell theories are not applicable

➢ **Membrane and bending behavior are modeled using a decoupled approach**



Schematic illustration of intra-ply deformation mechanisms

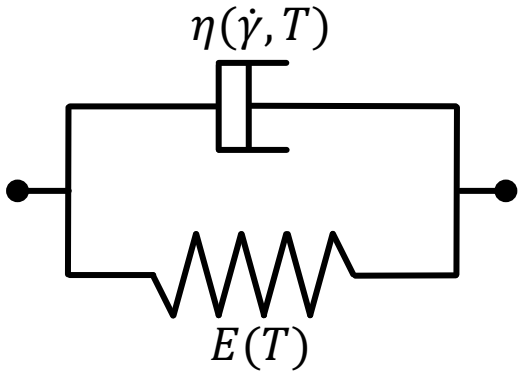


Schematic illustration of the decoupling of membrane and bending behavior

3. Material modeling & parameterization

Mechanical modeling molten material state

- **Nonlinear Voigt-Kelvin** approach is adopted for modeling both membrane and bending behavior

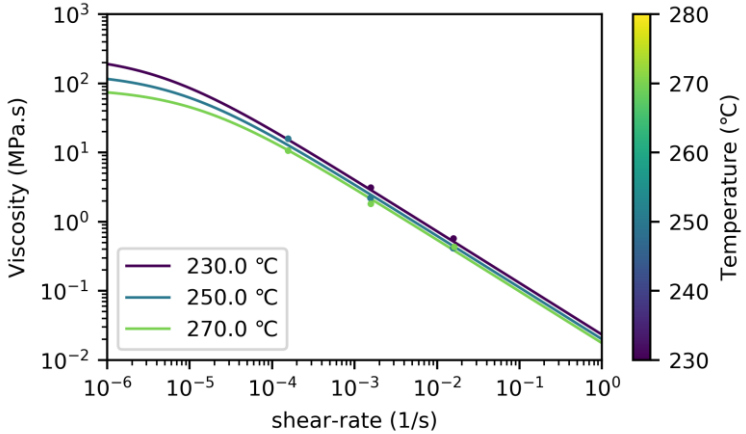


- Viscosity is described by **Cross-WLF** approach

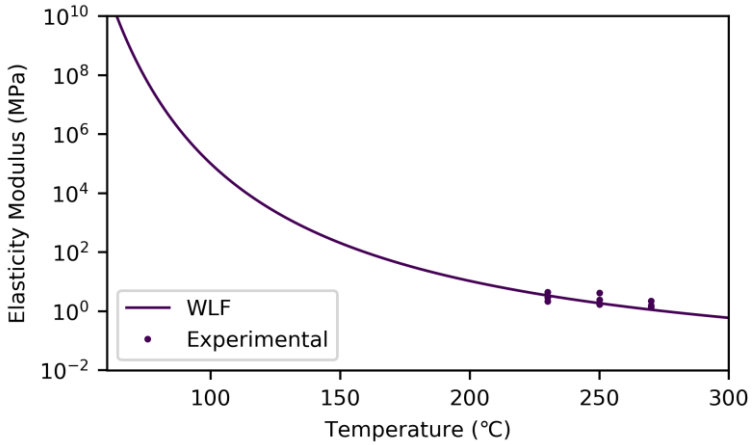
$$\eta(\dot{\gamma}) = \frac{\eta_0}{1 + \left(\frac{\eta_0 \dot{\gamma}}{\tau^*}\right)^{1-n}}$$

$$\eta_0(T) = D_1 \exp\left(\frac{A_1(T - D_2)}{A_2 + T - D_2}\right) \quad (1)$$

- Elasticity modulus is described by **WLF** approach, in analogy to viscosity (1)



Parameterization result (rheometer bending) for the viscosity $\eta(\dot{\gamma}, T)$ (Cross-WLF)



Parameterization result (rheometer bending) for elasticity modulus $E(T)$ (WLF)

3. Material modeling & parameterization

Thermal modeling

- The governing equation for thermal behavior is the **heat balance equation:**

$$\underbrace{\int_{\Omega}(\rho c_p \dot{T}\delta T)dV}_{\delta W^{\mathrm{cap}}} = \underbrace{\int_{\Omega}(\lambda \cdot \mathrm{grad}(T)) \cdot (\mathrm{grad}(\delta T))\mathrm{d}V}_{\delta W^{\mathrm{cond}}} + \underbrace{\int_{\Gamma_{\Omega}}(r\delta T)\mathrm{d}A}_{\delta W^{\mathrm{source}}} - \underbrace{\int_{\Omega}(s\delta T)\mathrm{d}A}_{\delta W^{\mathrm{surf}}}$$

- The different **thermal effects** are modeled as different **mechanisms**:

Intra-ply mechanisms

- Heat capacity[1]: δW^{cap}
- In-plane heat conductivity[1]: δW^{cond}
- Latent crystallization heat: $\delta W^{\mathrm{source}}$

Inter-ply mechanisms

- **Inner plies:**
  - Out-of-plane heat conductivity[1]
- **Outer plies:**
  - Tool-ply conductivity[1]
  - Convection and radiation[1]

[1]Xu et al.: CHARACTERIZATION OF HEAT TRANSFER PARAMETERS IN THE COMPRESSION MOLDING OF GLASS MAT THERMOPLASTICS, SPE ACCE 2020 Conference Proceedings.

3. Material modeling & parameterization

Crystallization kinetics modeling

- **Relative crystallinity** α describes transition from molten ($\alpha = 0$) to the solid material ($\alpha = 1$) state

- **"Differential Scanning Calorimetry"** (DSC) is adopted for characterization of crystallization kinetics

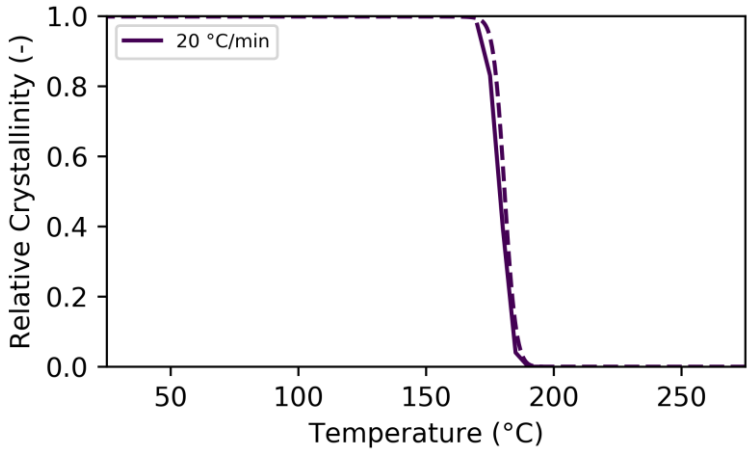
- **Modeling** of crystallization kinetics [6]:
  - Nakamura's equation for relative crystallinity:

$$\dot{\alpha} = nK(T)\big(1 - \alpha(t)\big)\ln\Big(-\big(1 - \alpha(t)\big)\Big)^{\frac{n-1}{n}}$$

  - Ziabicki's empirical approach:

$$K(T) = K_{\max}\exp\left(\frac{-4\ln(2)\,(T - T_{\max})}{D^2}\right)$$

  ➢ Material parameters $K_{\max}$, $T_{\max}$, and D are defined as a function of cooling rate



Parameterization result for crystallization kinetics at 20 °C/min

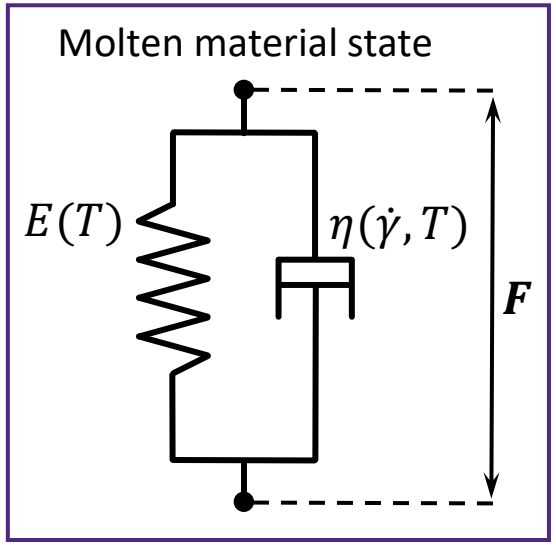
➢ **Phase transition** from molten to solid material sate is accurately captured

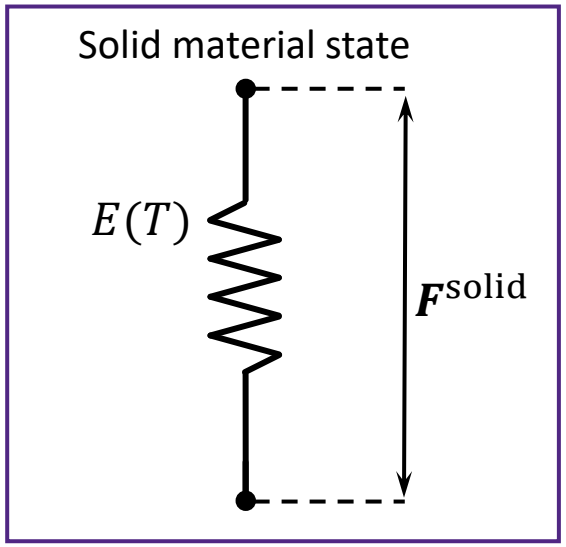
3. Material modeling & parameterization

Mechanical modeling phase transition

- The phase transition from molten to solid material state is accounted for in mechanical modeling:

$$\boldsymbol{\sigma} = (1-\alpha)\boldsymbol{\sigma}^{\text{molten}} + \alpha\boldsymbol{\sigma}^{\text{solid}}$$





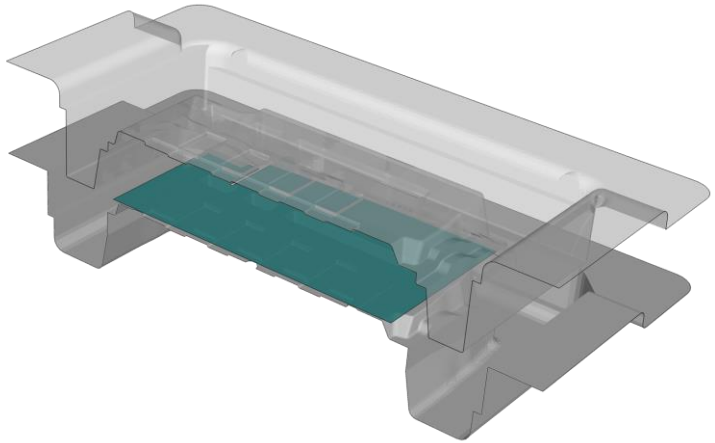
- **Molten material state:**
  - Nonlinear Voigt-Kelvin approach (Cross-WLF)
- **Solid material state**
  - Purely elastic approach
  - Full dissipation of elastic energy molten material state

4. Application to thermoforming simulation

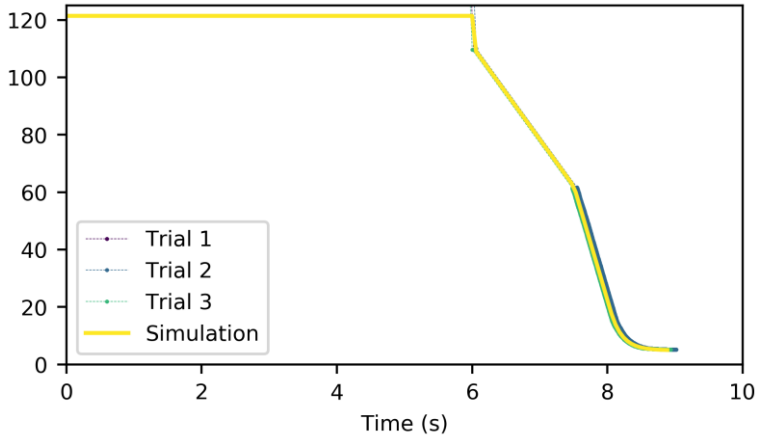
Model setup

- A complexly shaped geometry with several features is adopted as application example
  - Beads
  - Narrow deep draw areas
  - Local thickness changes

- Key data simulation model:
  - Rigid tool surfaces with constant temperature (150 °C)
  - Displacement-controlled forming (original press profile)
  - Initial laminate thickness: 2 mm
  - Initial laminate temperature:
    - Oven: 300 °C
    - Temperature after transfer determined through 1D thermal model[1]



Thermoforming simulation setup in cross-sectional view at the line of symmetry

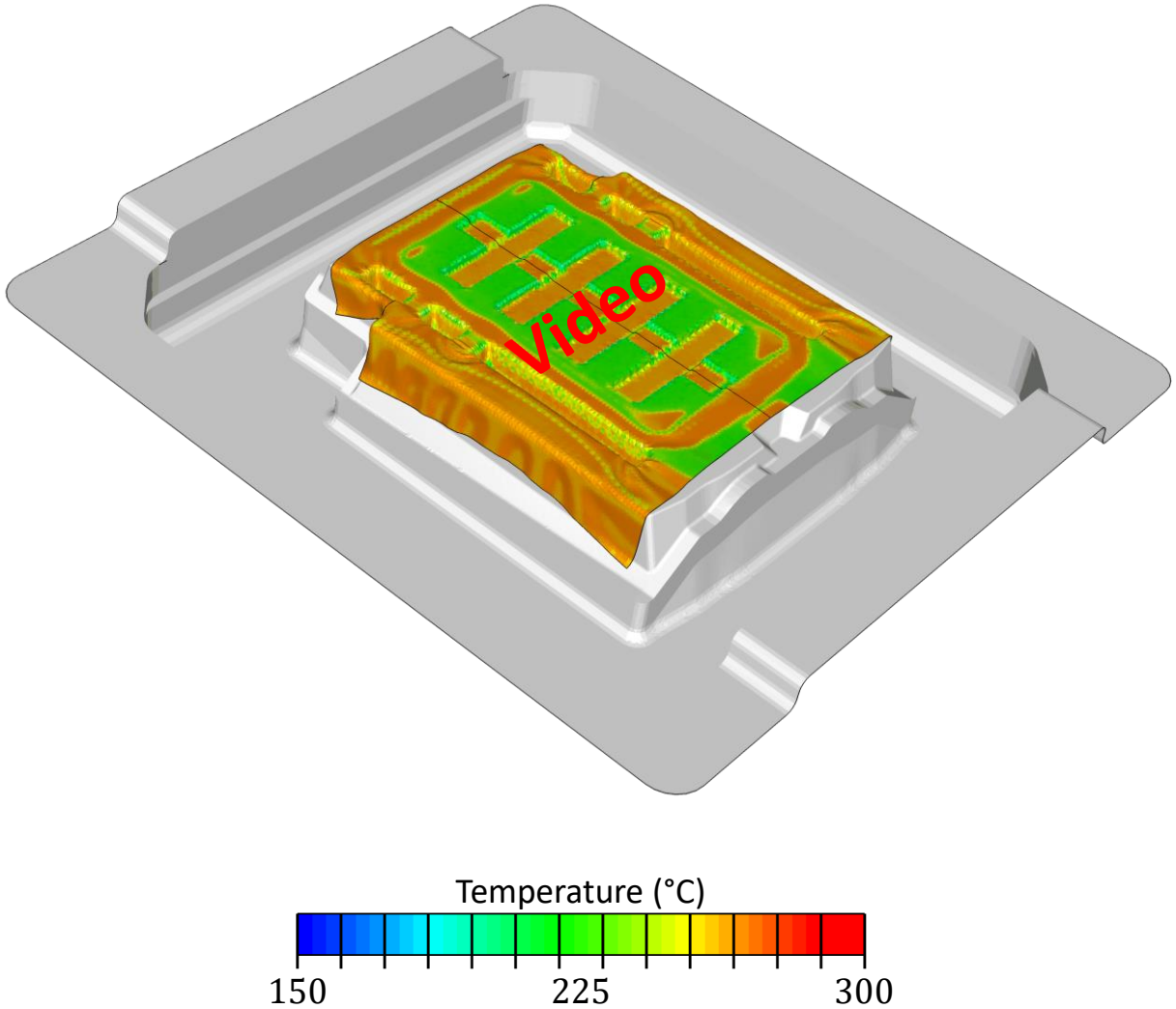


Press profiles in partial forming analysis (5 mm remaining tool travel)

[1]Xu et al.: CHARACTERIZATION OF HEAT TRANSFER PARAMETERS IN THE COMPRESSION MOLDING OF GLASS MAT THERMOPLASTICS, SPE ACCE 2020 Conference Proceedings.

4. Application to thermoforming simulation

Exemplary simulation result

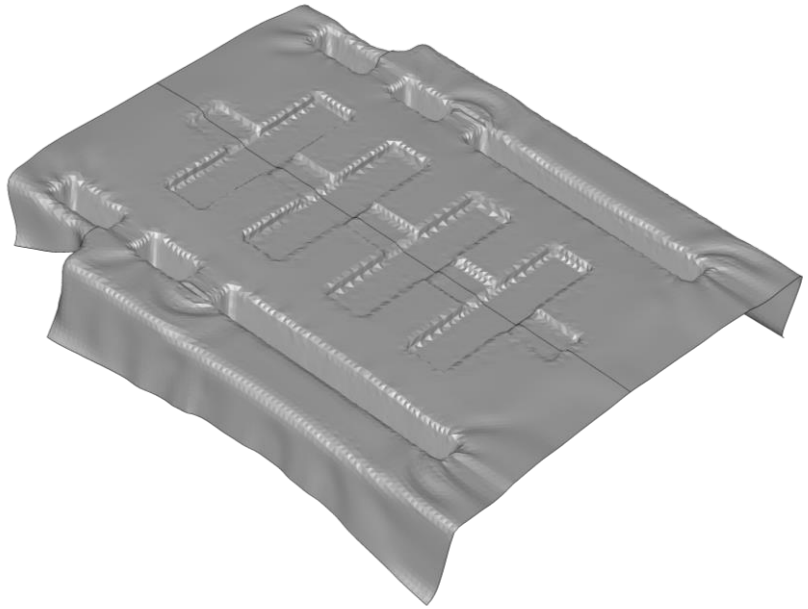


4. Application to thermoforming simulation

Validation

- **Experimental result:**

- **Simulation result:**



➢ **Wrinkling behavior is basically captured, but too loss pronounced**

5. Conclusion & outlook

Conclusion

- Thermoforming characterization approaches are successfully applied to a GMT material
  - Material behavior sensitive to shear-rate and temperature
- Testing of thin specimens in torsion bar and rheometer bending tests yields similar results
  - Decoupling of membrane and bending behavior not strictly necessary for GMT materials
- Thermomechanical thermoforming simulation basically captures the wrinkling behavior observed in experimental tests

Outlook

- Further refinement of mechanical and thermal parameterization
- Further development of the thermoforming approach to a 3D thermomechanical approach
  - Prediction of local thickness changes
- Development of a “Coupled Eulerian Lagrangian” (CEL) approach:
  1. Compression molding simulation
  2. Sequential thermoforming and compression molding simulation
- Industrialization of the developed methods by SIMUTENCE GmbH (KIT spin-off company)

References

1. Sachs U, Akkerman R. Viscoelastic bending model for continuous fiber-reinforced thermoplastic composites in melt. Composites Part A: Applied Science and Manufacturing(100):333–41.
2. Haanappel SP, Akkerman R. Shear characterisation of uni-directional fibre reinforced thermoplastic melts by means of torsion. Composites Part A: Applied Science and Manufacturing 2014;56:8–26.
3. Dörr D. Simulation of the thermoforming process of UD fiber-reinforced thermoplastic tape laminates, Doctoral thesis, Karlsruhe Institute of Technology (KIT), Institute of Vehicle System Technology (FAST), 2019.
4. Dörr D, Joppich T, Henning, F., Kärger, L. A coupled thermomechanical approach for finite element forming simulation of continuously fiber-reinforced semi-crystalline thermoplastics. Composites Part A: Applied Science and Manufacturing 2019(125):105508.
5. Dörr D, Schirmaier FJ, Henning F, Kärger L. A viscoelastic approach for modeling bending behavior in finite element forming simulation of continuously fiber reinforced composites. Composites Part A: Applied Science and Manufacturing 2017;94:113–23.
6. Kugele D, Dörr D, Wittemann F, Hangs B, Rausch J, Kärger L, Henning F. Modeling of the non-isothermal crystallization kinetics of polyamide 6 composites during thermoforming. AIP Conference Proceedings 1896, 2017.

SPE ACCE 2020

On the Applicability of Thermoforming Characterization and Simulation Approaches to Glass Mat Thermoplastic Composites

D. Dörr, R. Gergely, S. Ivanov, L. Kärger, F. Henning, A. Hrymak

July 3, 2020

Contact details:

Dr.-Ing. Dominik Dörr

Email: ddoerr@uwo.ca

Mobile: +49-179-4205169

Western Engineering

Department of Mechanical & Materials Engineering

Western

UNIVERSITY · CANADA