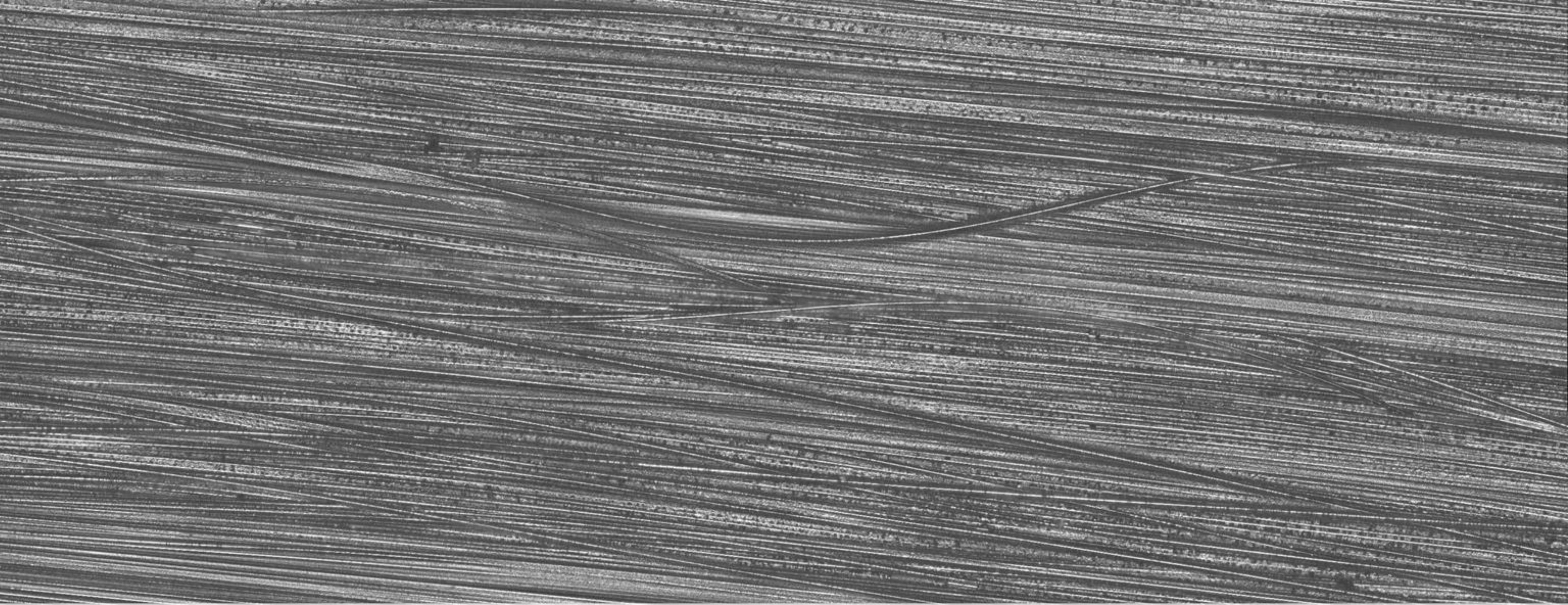


Understanding and modeling of the ply-ply friction response for UD C/PAEK tapes in melt

Rens Pierik – FPCM Conference – June 29, 2023
Wouter Grouve, Sebastiaan Wijskamp, Remko Akkerman

TPRC

UNIVERSITY OF TWENTE.

UNDERSTANDING AND MODELING PLY-PLY FRICTION

Contents:

- Introduction hot press forming and ply-ply friction
- Experimental work
- Modeling:
  - Peak and long-time shear stress
  - Transient friction curve
- Conclusion

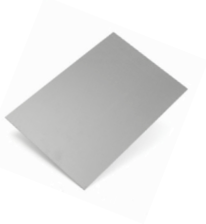
TPRC

INTRODUCTION

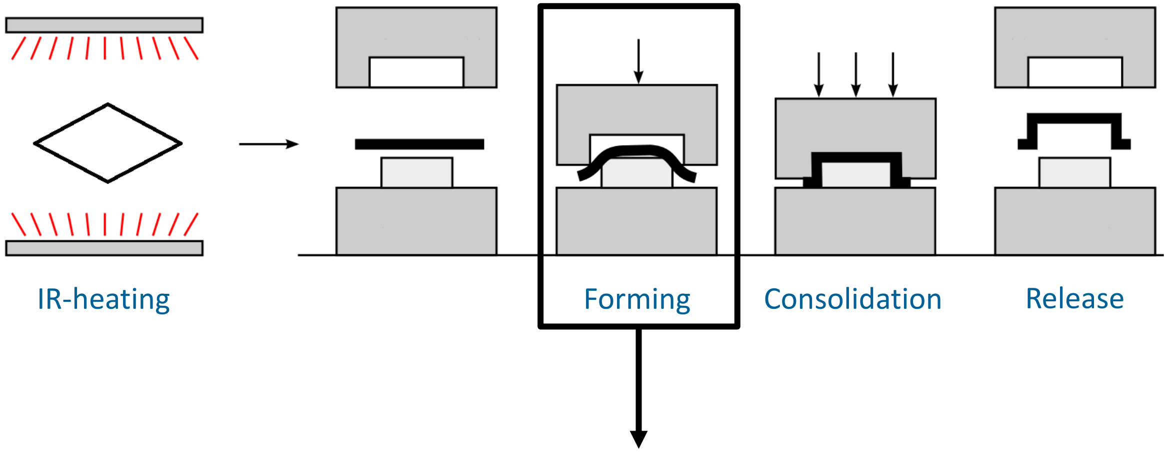
Manufacturing composite parts

- Hot press forming of thermoplastic composites:

Continuous fiber reinforced tape



Pre-consolidated laminate

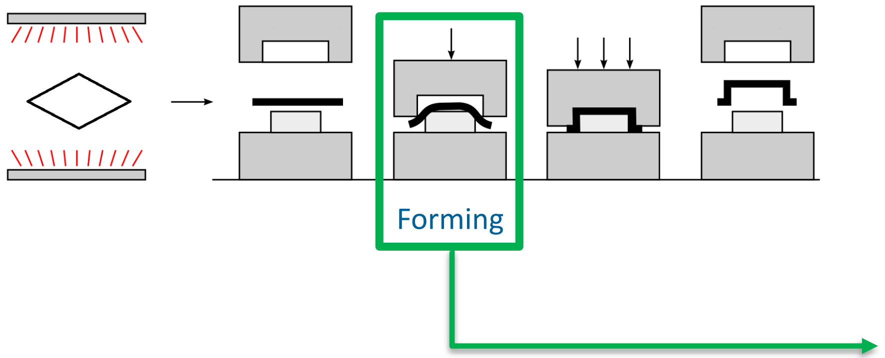


- Lightweight structures
- High volumes at low cost

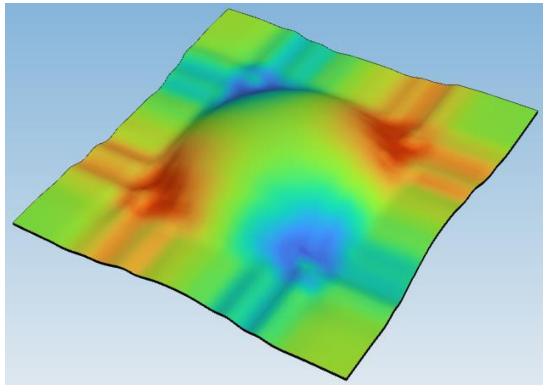
Wrinkling could occur…

INTRODUCTION

Simulation software



Simulation software



→ Virtually change design
Avoid trial-and-error
Complex shapes & materials

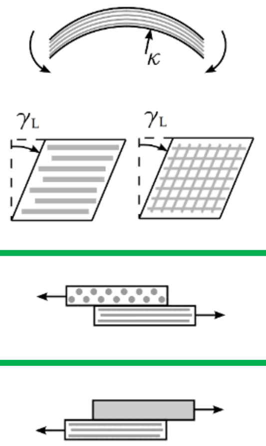
But predictions need to be accurate… especially problem for UD reinforcements

Haanappel (2013). PhD thesis, University of Twente.

INTRODUCTION

Strategy

- Process simulation software:
  - Mathematical description of deformation mechanisms



- Bending
- Intra-ply shear
- Ply-ply friction
- Tool-ply friction

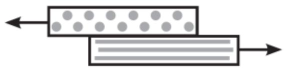
More advanced modelling and characterization

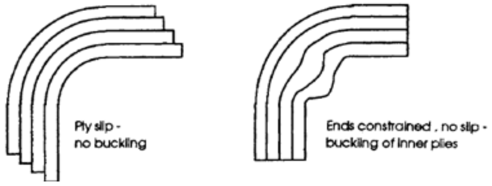
⇒ **Improve predictive quality**

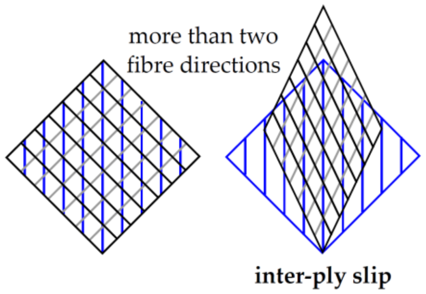
Sachs (2014). Friction and bending in thermoplastic composites forming processes

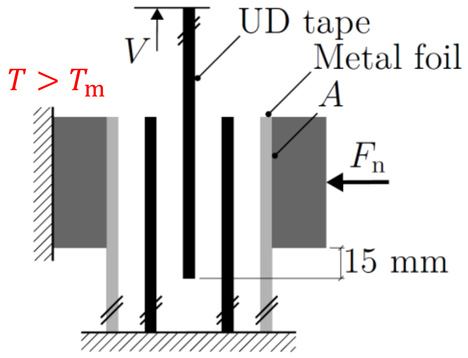
INTRODUCTION

Ply-ply friction

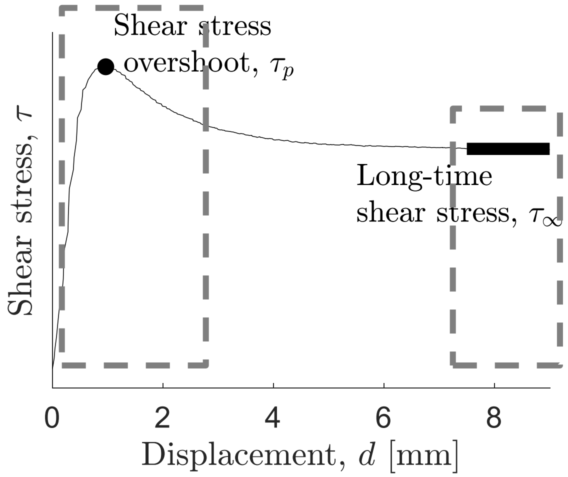








- *Situation:* ply-ply friction
  - Relative movement between successive plies
  - Friction tester to characterize response
- *Complication:*
  - Often only τ_∞ considered…
  - Most slip lengths in simulations correspond to transient regime
- *Questions:*
  - What is the underlying mechanism for the friction response?
  - Can we model the transient friction response?

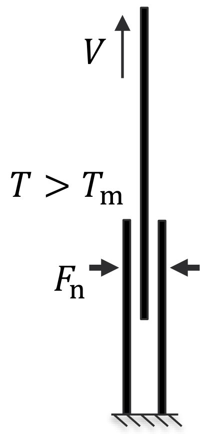


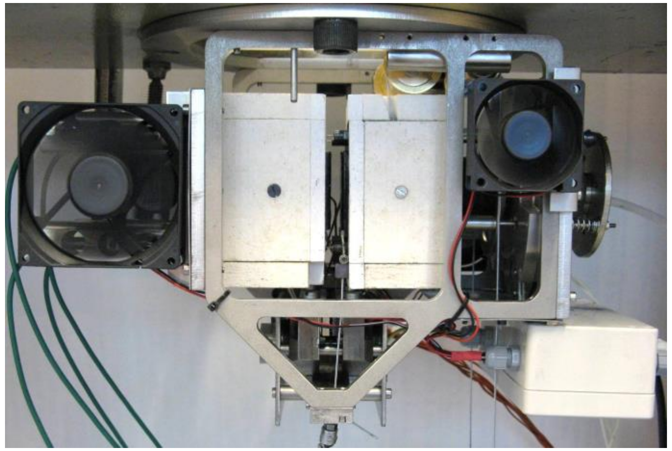
Sachs (2014). PhD thesis, University of Twente. Murtagh et al (1995). Comp. Manuf. 6, 169-175. Haanappel (2013). PhD thesis, University of Twente.

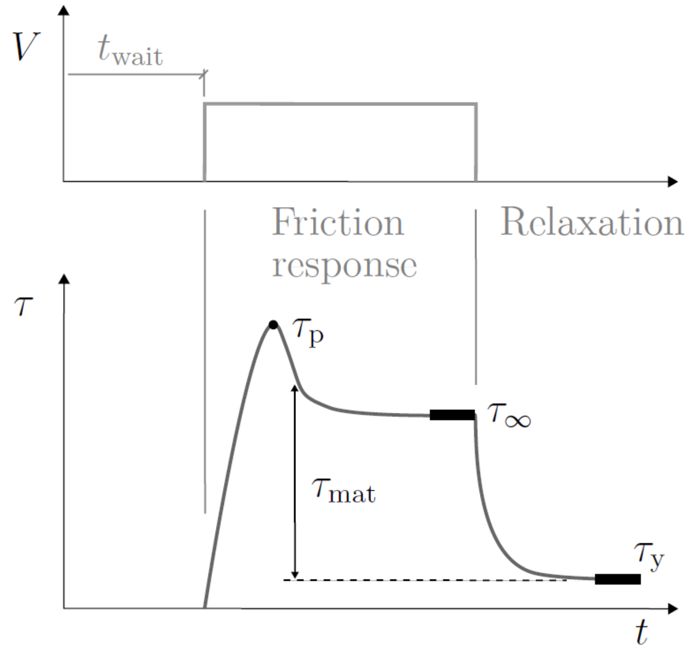
EXPERIMENTAL WORK

Ply-ply friction tests

- Material:
  - Toray TC1200 UD C/PEEK (59% V_f)
  - Processing T: 370-400 °C
  - 0°/0° lay-up in specimen
- Experimental conditions:
  - Constant T of 385 °C and p of 15 kPa
  - Range of sliding rates V: 1-200 mm/min
  - 5 minute heating time



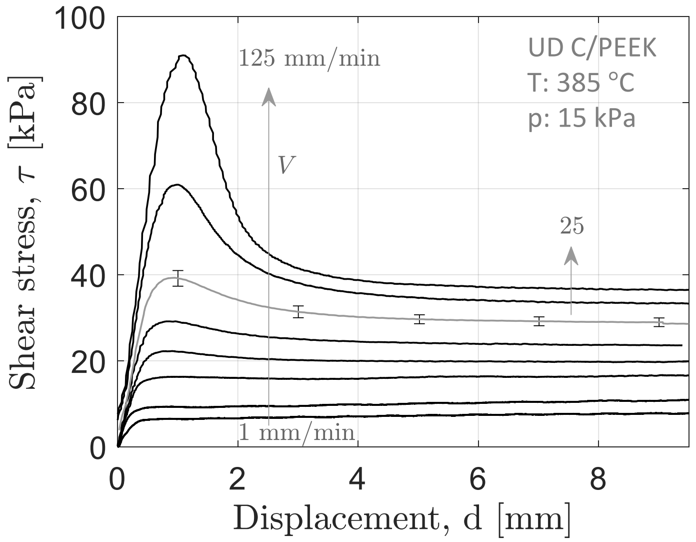




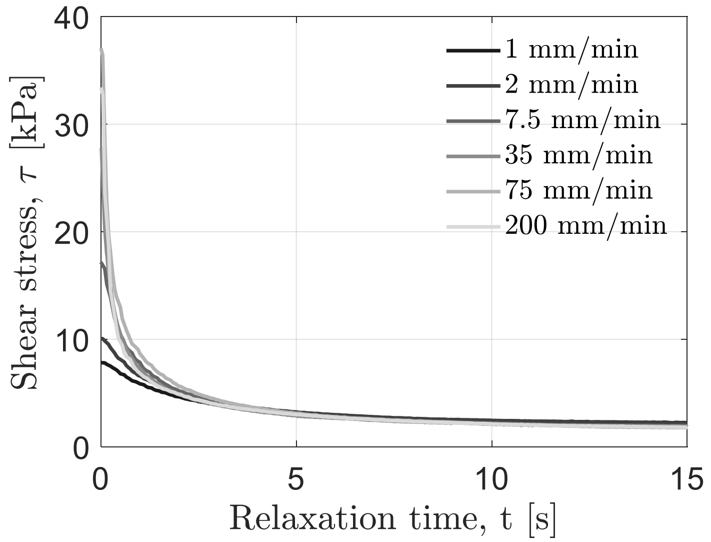
EXPERIMENTAL WORK

Ply-ply friction tests

- Friction response:
  - Peak increases with increasing sliding rate V
  - τ_∞ bounded at limiting value



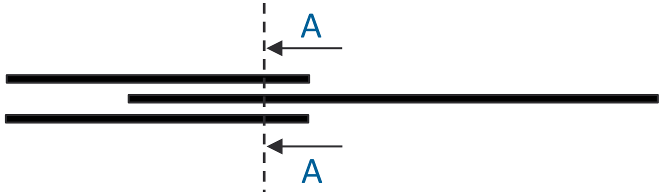
- Stress relaxation:
  - Stress drops after sliding action stopped
  - Residual after 'full' relaxation



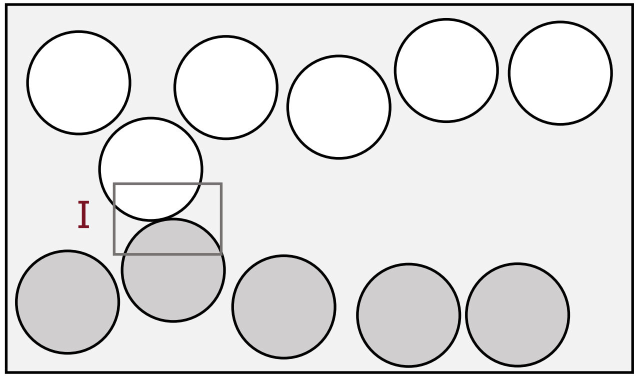
Pierik et al. (2021). Proceedings of 24th International Conference of Material Forming, Liege, Belgium, 3695.

EXPERIMENTAL WORK

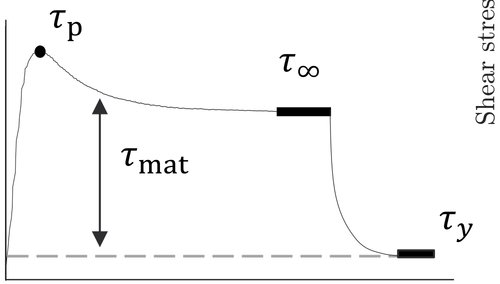
Fiber-fiber interaction

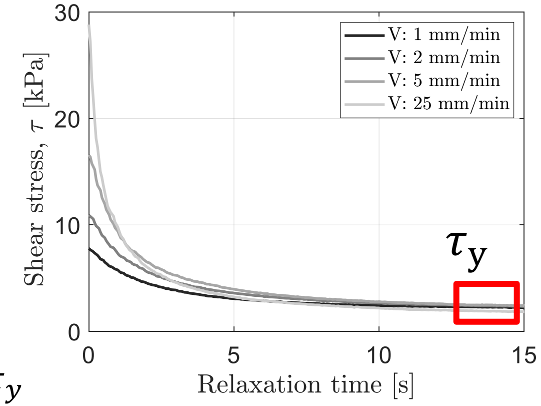


Ply-ply cross-section



- Ply-ply cross-section:
  - Matrix interlayer in melt
  - Fiber-fiber contact
- Fiber interactions:
  - Could result in residual stress
- Distinguish VE matrix response τ_{mat} and static yield stress τ_{y} from total response

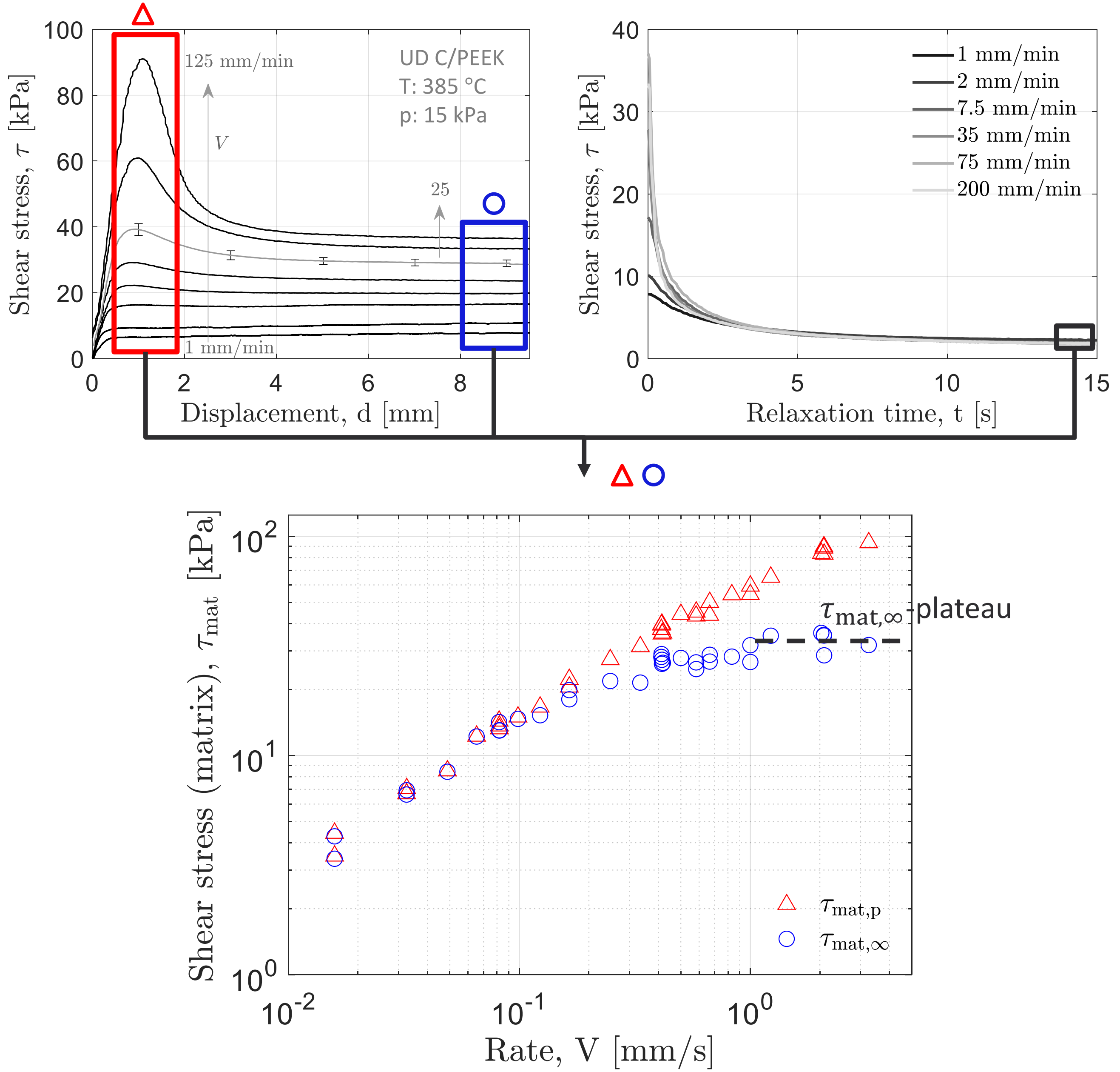




Murtagh et al. (1993), in: A. Miravete (Ed.), Proceedings of ICCM-9, Madrid, Spain, pp 311-318. Cogswell (1992). Thermoplastic Aromatic Polymer Composites, UK: Butterworth-Heinemann.
Advani et al. (1997), Chapter 8 in: D. Bhattacharyya (Ed.), Composite Materials Series, vol. 11, Elsevier, pp 323-369.

EXPERIMENTAL WORK

Flow curve



- Flow curve:
  - Characteristics of friction response with rate
  - $\tau_{\mathrm{mat,p}}$ increases with V
  - $\tau_{\mathrm{mat},\infty}$-plateau emerges

- What about $\tau_{\mathrm{mat,p}}$ and $\tau_{\mathrm{mat},\infty}$?

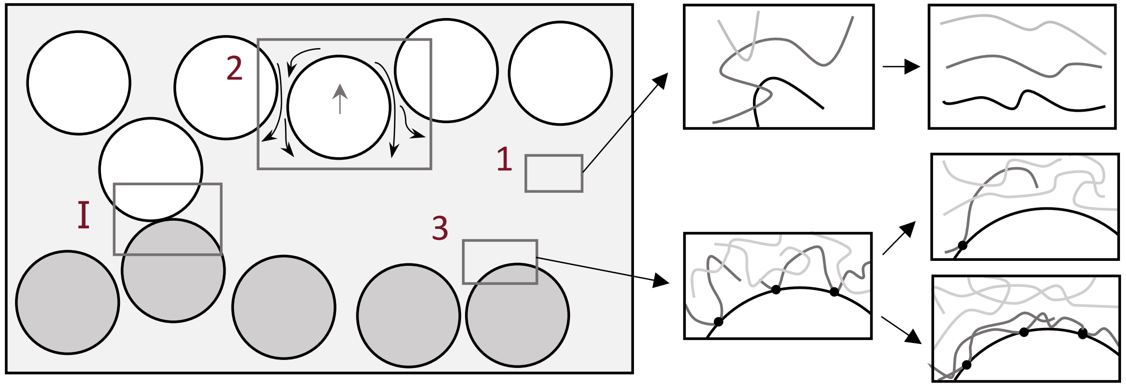
MODELING WORK

Hypotheses

- Hypotheses for transient (matrix) response:
  1. Nonlinear viscoelasticity
  2. Increase matrix interlayer thickness
  3. Slip relaxation effect (wall slip)

- All revolve around some kind of shearing action in matrix interlayer at ply-ply interface…

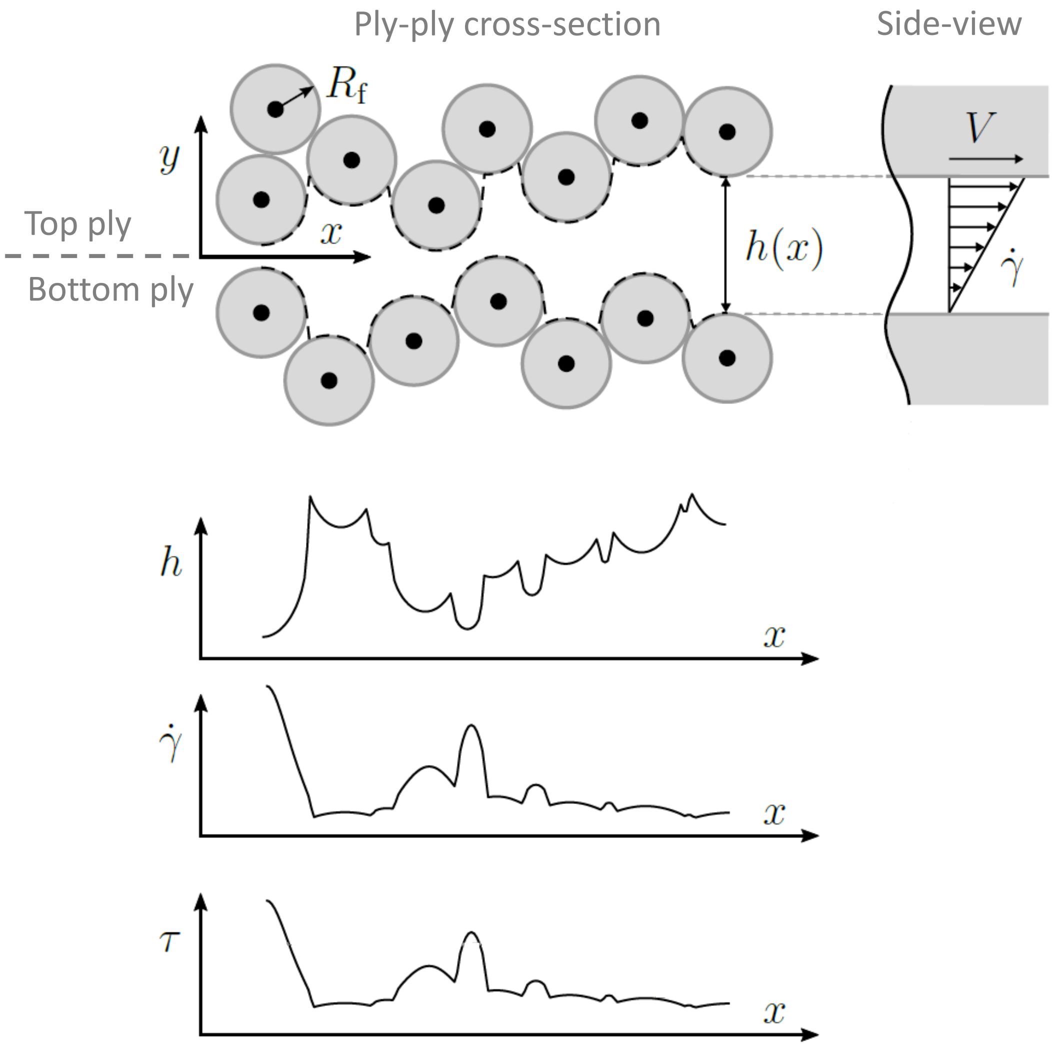
Ply-ply cross-section



MODELING WORK

Shear flow model

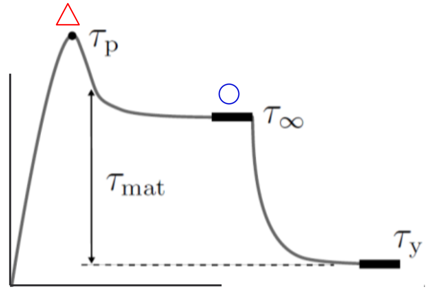
- Model friction at ply-ply interface:
  - Assuming 1D shear flow of matrix material
  - No interference of flow in width direction
  - Matrix interlayer thickness distribution $h(x)$
  - Viscous flow:
    - $\tau_{\text{visc}}(x) = \eta\left(\frac{V}{h(x)}\right)\frac{V}{h(x)} \quad \Rightarrow \quad \tau_{\text{avg}} = \frac{1}{w}\int_0^w \tau_{\text{visc}}(x)\,dx$
- Model inputs:
  - Matrix viscosity from plate-plate rheometry
  - Matrix interlayer thickness distribution $h(x)$ from micrographs or generated fiber distr.



Pierik et al. (2022). Compos. Part A: App Sci and Manuf 163, 107185.
Melro et al (2008). Compos. Sci. Tech., 68, 2092-2102.

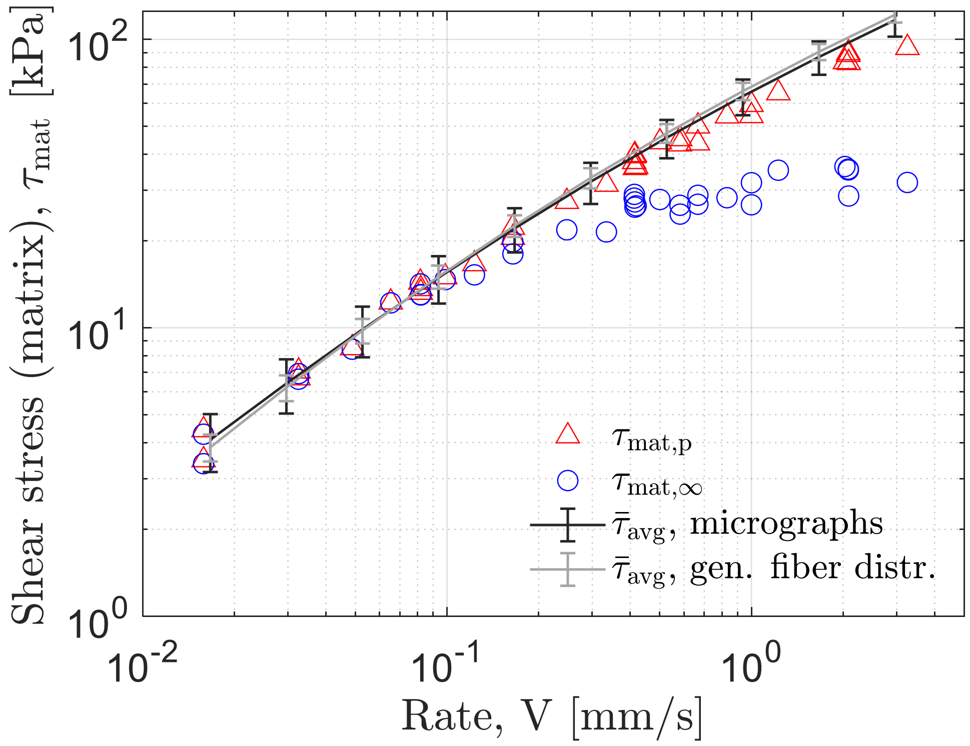
MODELING WORK

Comparison model and measurement



- Prediction of peak shear stress $\tau_{mat,p}$:
  - 16 (smoothed) $h(x)$ from micrographs
  - 10 generated fiber distributions
- Good agreement model ($\bar{\tau}_{avg}$) & measurement
- Recall hypotheses to model $\tau_{mat,\infty}$:
  - (Wall) slip relaxation effect most probable
  - Literature on polymer melts: rate jump (stress-contr.) or stress plateau (rate-contr.) at critical shear stress

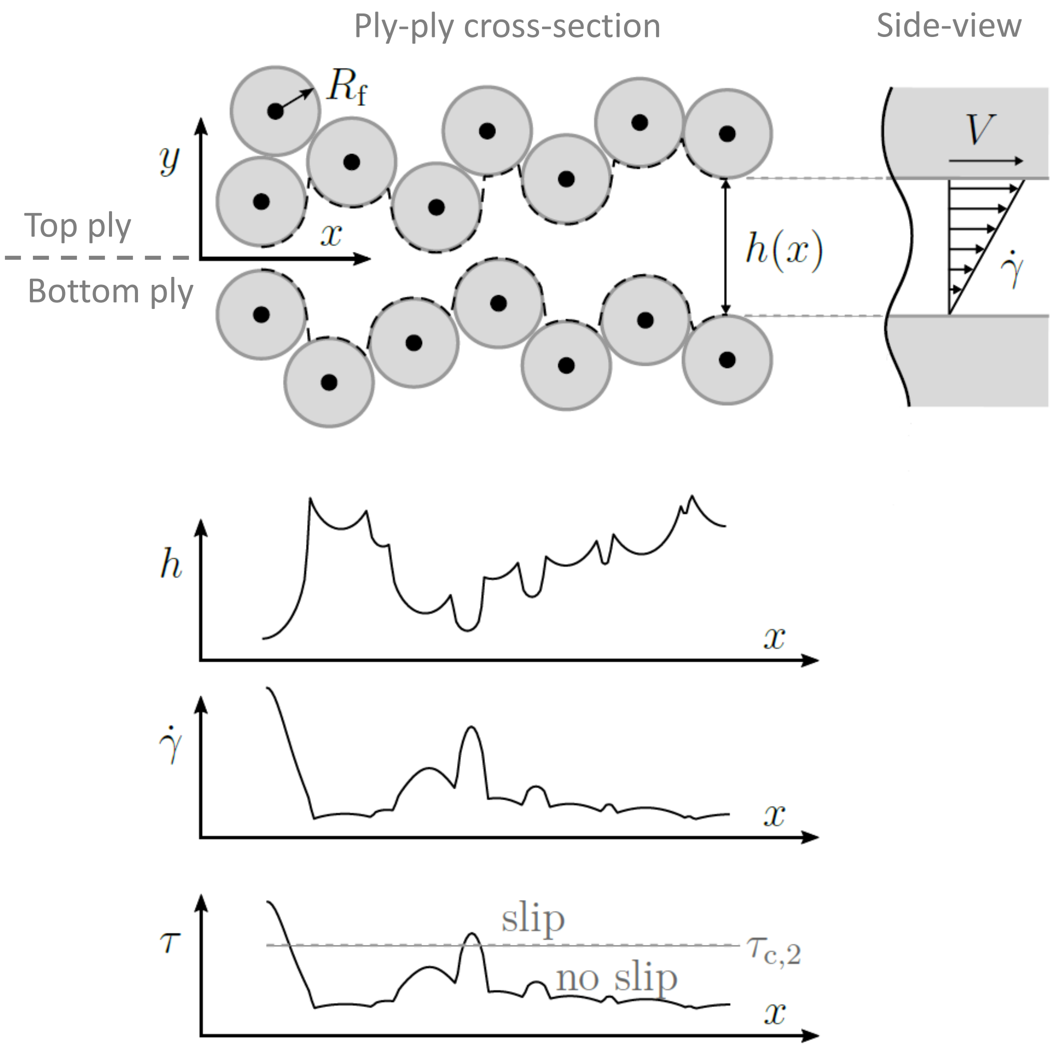
Toray C/PEEK, 385 °C, 15 kPa



Hatzikiriakos (2012) Prog Polym Sci 37, Boukany et al (2009) Macromolecules 42, Park et al (2008) J Rheol 52.

MODELING WORK
Shear flow model

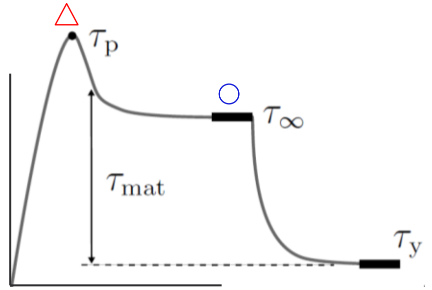
- Recall the shear flow model:
  - Viscous flow of matrix material at ply-ply interface
- Include (strong) wall slip:
  - Use $\tau_{c,2}$ as a limiting value
  - Bound viscous shear stress distribution:
    - $\tau_{visc}(x) = \min\left[\eta\left(\frac{V}{h(x)}\right)\frac{V}{h(x)}, \tau_{c,2}\right]$
  - Base $\tau_{c,2}$ on experimental results: $\tau_{mat,\infty}$-plateau



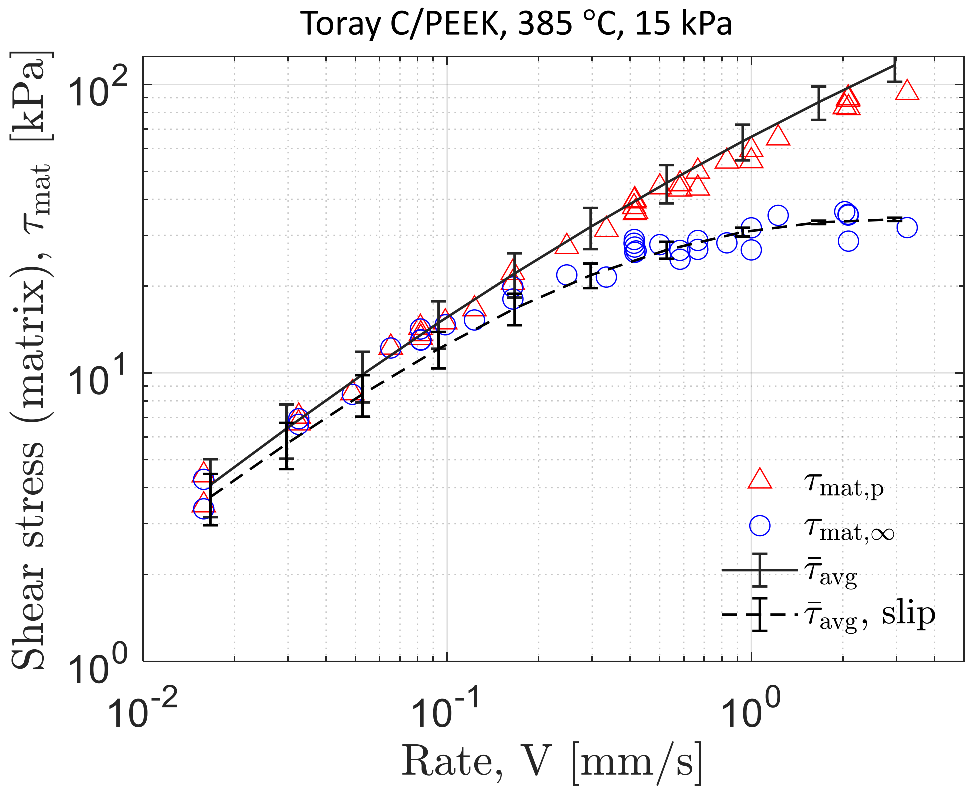
Hatzikiriakos et al (1992) J Rheol 36, Boukany et al (2009) Macromolecules 42, Park et al (2008) J Rheol 52.

MODELING WORK

Shear flow model



- Good agreement modeled and measured long-time shear stress $\tau_{mat,\infty}$
- Gradual transition from no-slip to full-slip with sliding rate due to h
- Combined experimental and modeling work substantiate concept of wall slip

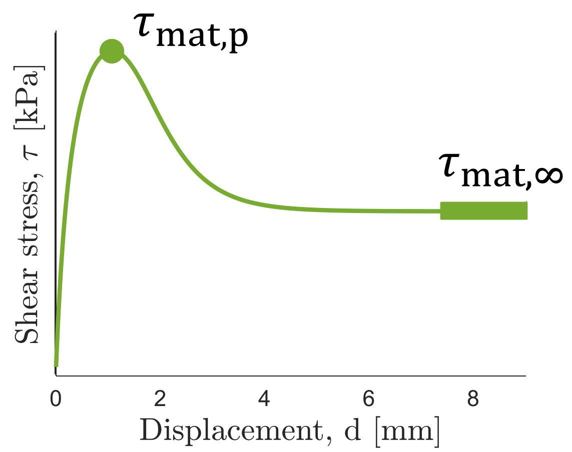


Pierik et al. (2022). Compos. Part A: App Sci and Manuf 163, 107185.

FULL TRANSIENT MODELING

The next step

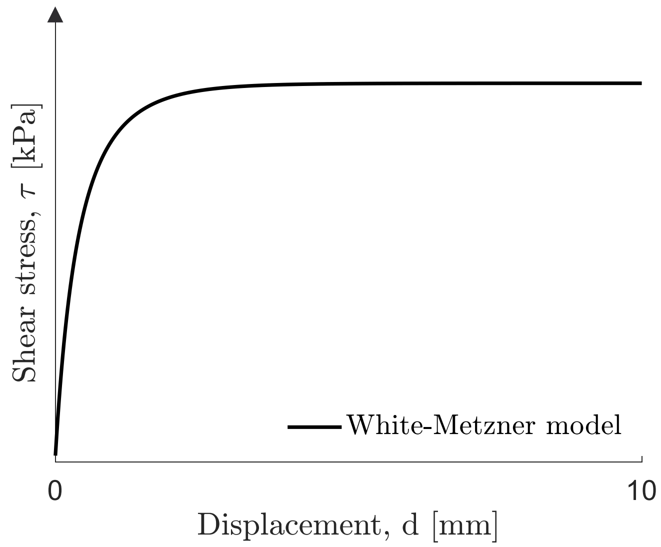
- What we have:
  - Model for characteristics of friction response
- What we want:
  - Describe the full transient response,
    but no too computationally expensive…
- How?
  - Further explore the identified underlying mechanisms…



FULL TRANSIENT MODELING

Conceptualization

- Proposed mechanisms:
  1. Shear flow of matrix material at ply-ply interface
  2. Wall slip relaxation effect at fiber-matrix interface



1. Shear flow of matrix material:
   - Viscoelastic model for stress growth with $\eta(\dot{\gamma})$ and $h(x)$
   - White-Metzner model:

$$\tau_{12} + \lambda(\dot{\gamma})\frac{\mathrm{d}\tau_{12}}{\mathrm{d}t} = \eta(\dot{\gamma})\dot{\gamma} \quad \text{with} \quad \lambda(\dot{\gamma}) = \frac{\eta(\dot{\gamma})}{G_{\mathrm{WM}}} \text{ and } \dot{\gamma} = \frac{V}{h(x)}$$

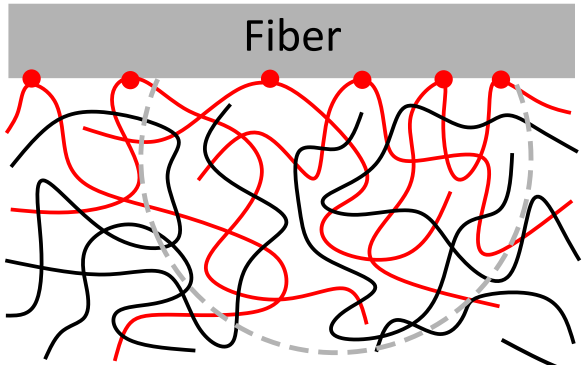
   - Adjust shear rate for wall slip

White, Metzner (1983). J. of Appl. Polym. Sci., 7 (5), 1867-1889.

FULL TRANSIENT MODELING

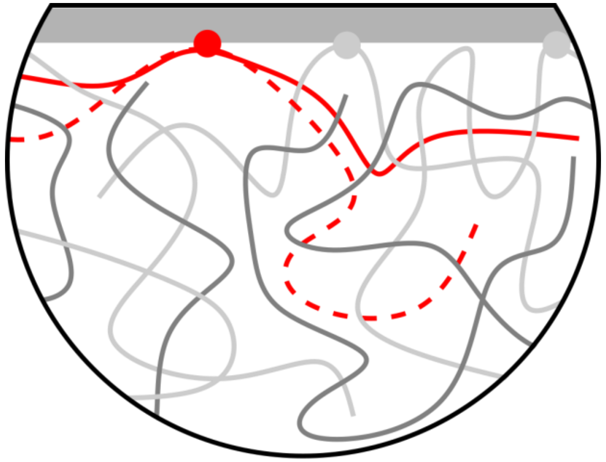
Conceptualization

2. Wall slip relaxation effect:
   - Transition from no-slip towards fully-developed wall slip at high rates
   - Critical shear stress $\tau_{c,2}$ for onset of wall slip
   - Proposed slip mechanism: disentanglement

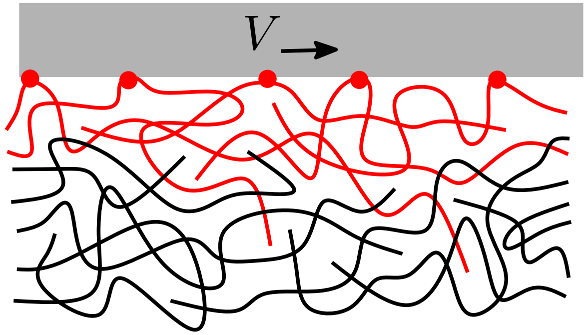


Rest state; surface chains (red) adsorbed to the wall (fiber) and entangled with bulk chains

Surface chains elongate and retract from bulk due to applied shear flow



Surface chains settle to new eq. state with less bulk interaction



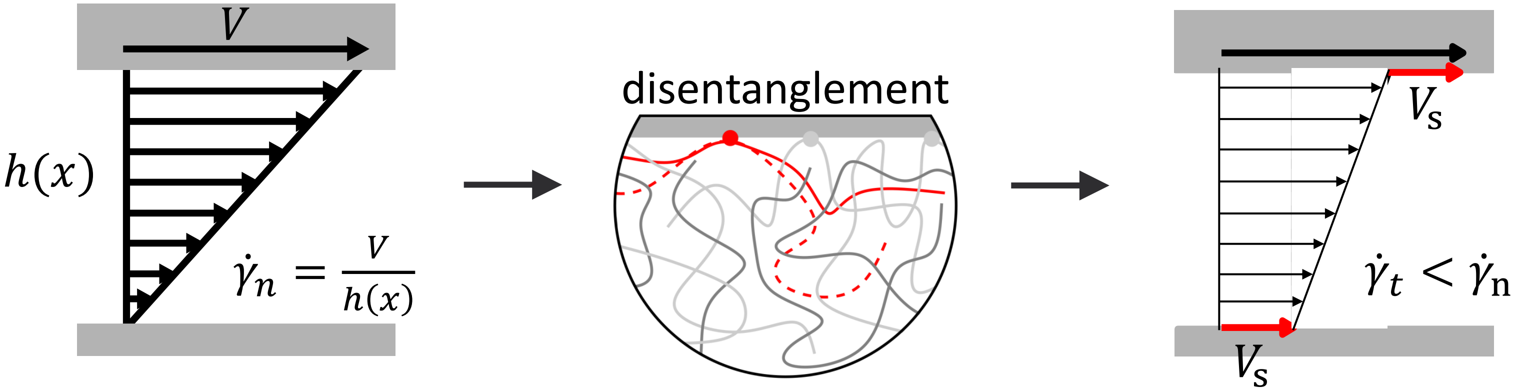
- *Eq. state corresponding to applied shear flow*
- *Still dis- and re-entanglement*
- *Less interaction, thus less momentum transfer*

Brochard, de Gennis (1992). Langmuir, 8 (12), 3033-3037.
Hatzikiriakos (2012). Progr. in Polym. Sci., 37 (4), 624-643.

FULL TRANSIENT MODELING

Conceptualization

2. Wall slip relaxation effect:
   - Slip velocity V_s emerges with ongoing deformation



- V_s to correct for the changing BC: $\dot{\gamma}_t = \frac{V-2V_s}{h(x)}$

  ⇒ Thus, now we just need to describe $V_s(t)$…

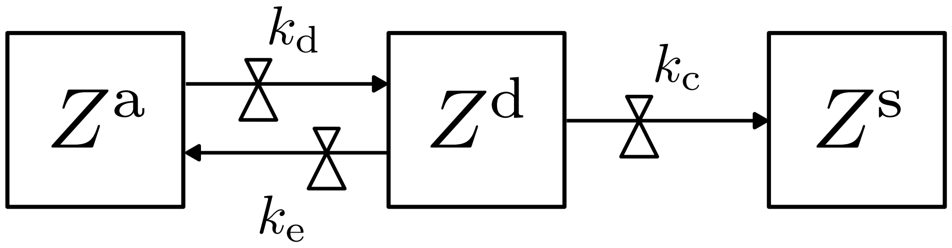
FULL TRANSIENT MODELING

The approach

- Idea: describe process of disentanglement with state-rate model

- Consider a relative number of active surface chains Z^a in the matrix-fiber interface
  1. In rest state, all surface chains interact with bulk through entanglements
     $\rightarrow Z^\mathrm{a}$ equals unity
  2. Upon shear deformation, surface chains retract to disentangled state Z^d with rate k_d

     A disentangled surface chain could:
     a. Relax and re-entangle with entanglement rate k_e
     b. Settle into equilibrium state Z^s corresponding to applied shear deformation with conformation rate k_c
  3. With $t \rightarrow \infty$, all surface chains settled and $Z^\mathrm{s} = 1$



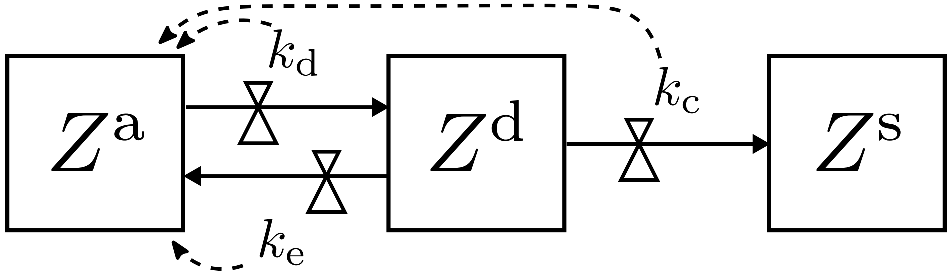
$$\frac{\mathrm{d}Z^\mathrm{a}}{\mathrm{d}t} = -k_\mathrm{d}Z^\mathrm{a} + k_\mathrm{e}Z^\mathrm{d}$$

$$\frac{\mathrm{d}Z^\mathrm{d}}{\mathrm{d}t} = k_\mathrm{d}Z^\mathrm{a} - k_\mathrm{e}Z^\mathrm{d} - k_\mathrm{c}Z^\mathrm{d}$$

$$\frac{\mathrm{d}Z^\mathrm{s}}{\mathrm{d}t} = k_\mathrm{c}Z^\mathrm{d}$$

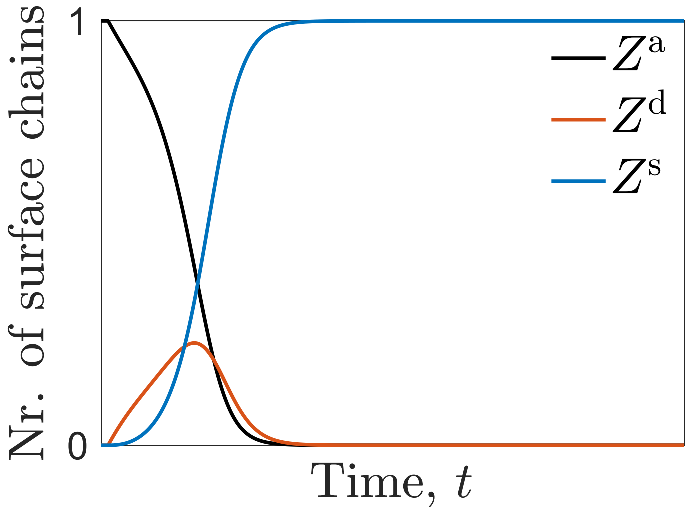
FULL TRANSIENT MODELING

State-rate model



- Rates k_i need to be determined…
  - Probably depend on states Z^i and V

- Use linear interpolation between k_min and $k_\mathrm{max} = k_\mathrm{min} + aV^m$ based on Z^a:
  - At start-up: low disentanglement k_d, high entanglement k_e
  - Conformation k_c same rate as k_d



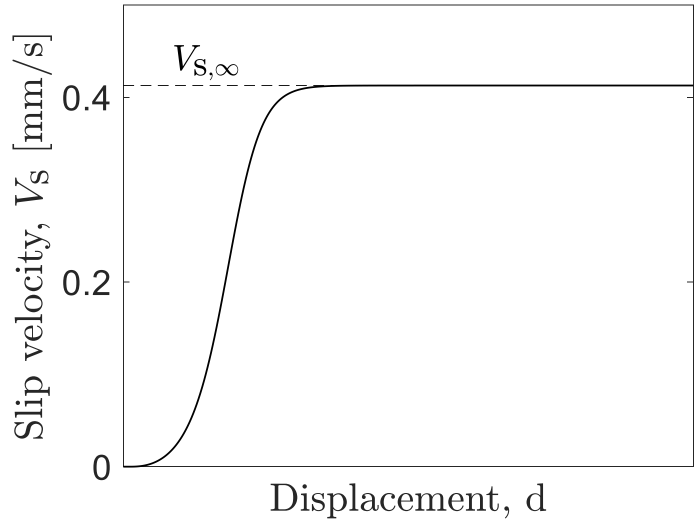
STATE-RATE MODEL

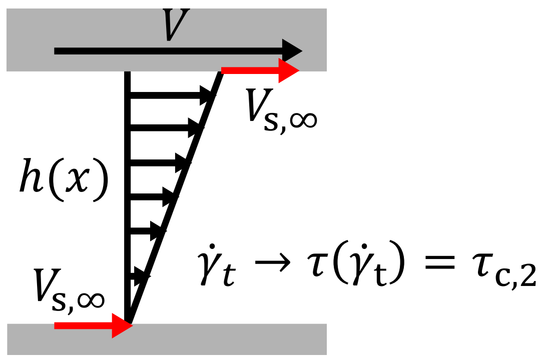
Implementation with V_s

- Relate evolution of Z^s to slip velocity:

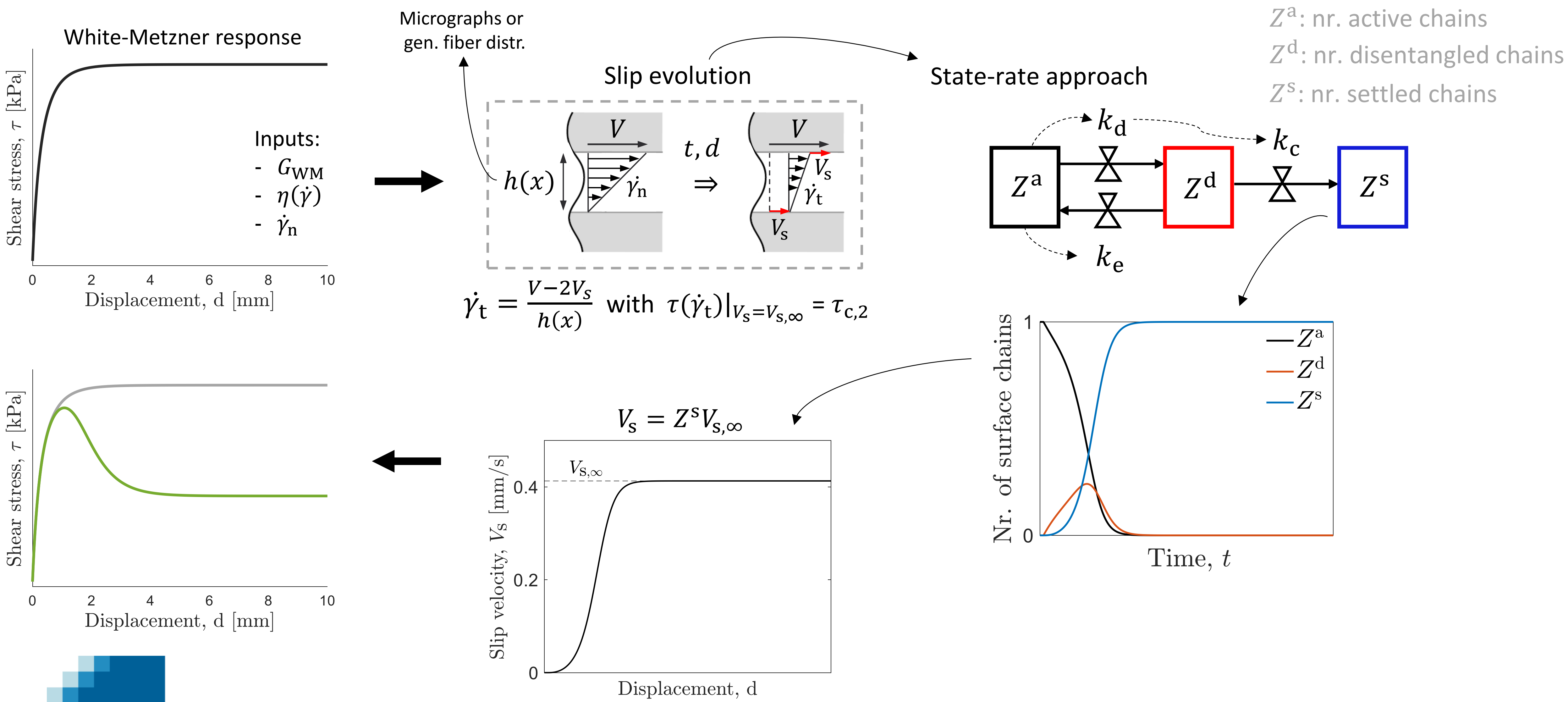
$$V_s(t) = V_{s,\infty} Z^s(t),$$

with $V_{s,\infty}$ the slip velocity in steady-state (VE shear stress = interfacial shear stress = $\tau_{c,2}$)





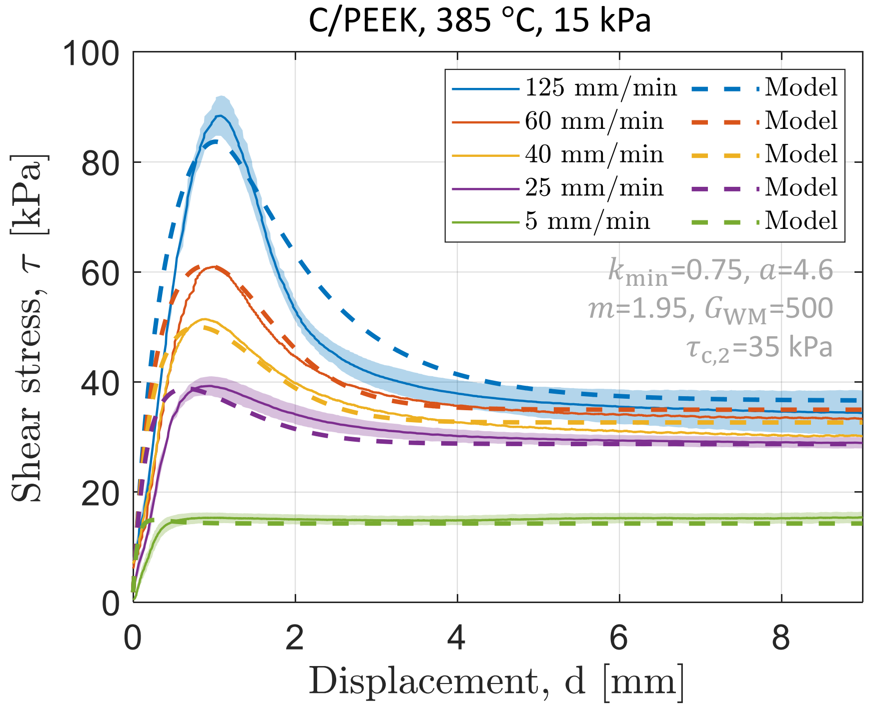
OVERVIEW FULL TRANSIENT MODELING

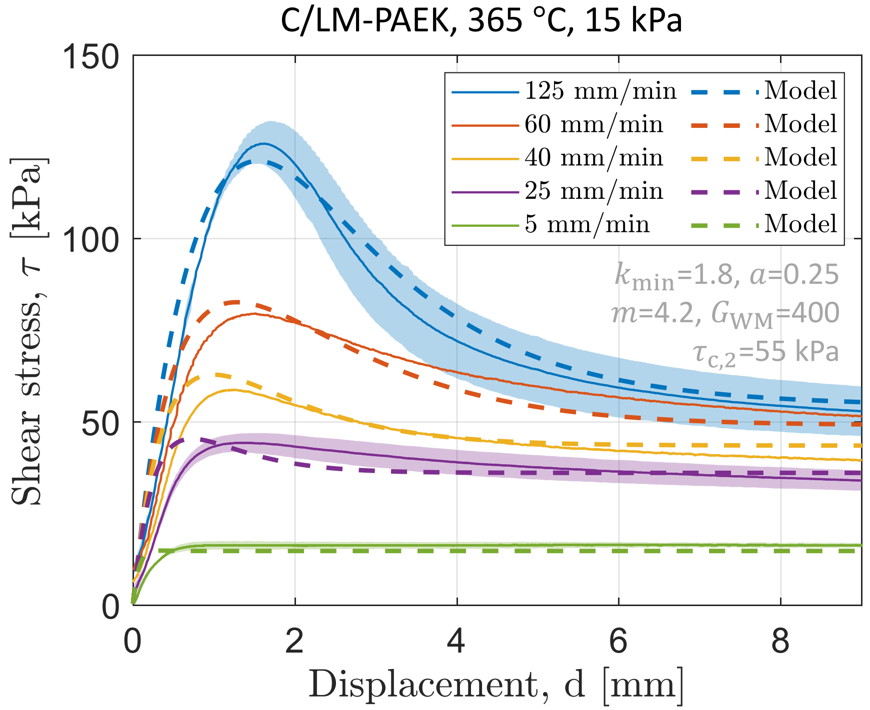


FULL TRANSIENT MODELING

Model & measurement

- Comparison model and measurement:





WRAP-UP

- Slip relaxation or gradual increase of wall slip explains the observed transient ply-ply friction response of UD TPC tape in melt, exhibiting a peak followed by steady-state friction
- The peak friction can be predicted by shear flow of matrix material at the ply-ply interface
- The steady-state friction can be predicted through including a critical shear stress for the onset of (strong) wall slip
- The full transient (start-up) friction response can be captured with VE framework combined with a state-rate model that describes the evolution of the slip velocity at the fiber-matrix interface
- Future work is to implement the proposed transient shear flow model in simulation software

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NWO

Thank you for your attention!

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