

Ply–Ply and Tool–Ply Friction of C/LMPAEK in the Melt State

Influence of Fiber Orientation

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Enschede, the Netherlands

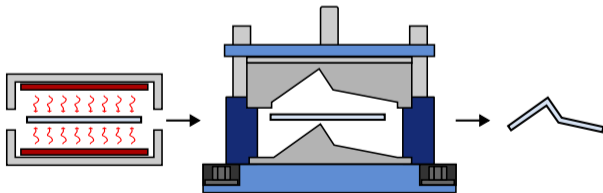
June 30th, 2026

Sheffield, UK

Press forming

High-rate manufacturing for composite components

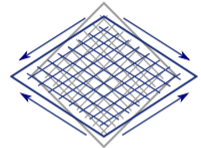
- Press forming is an attractive high-rate manufacturing process for **thermoplastic composites** (TPCs)
- The **limited formability** of TPCs gives rise to processing **defects**, like folds, wrinkles or ply splits



Forming simulations

Right-first-time manufacturing

- FE simulations are used to **predict** the formation of defects in advance
- Typically, the material behavior is decomposed into several **deformation mechanisms**, e.g. in-plane shear, bending, and ply slippage



in-plane shear



bending



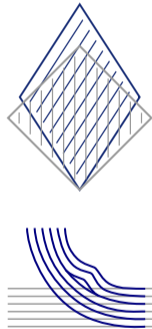
slippage

Forming simulations

Right-first-time manufacturing

- FE simulations are used to **predict** the formation of defects in advance
- Typically, the material behavior is decomposed into several **deformation mechanisms**, e.g. in-plane shear, bending, and ply slippage
- Suppression of ply slippage can lead to defects
- The resistance to ply slippage, or **friction**, is essential input to press forming simulations

interply slip



Interply friction

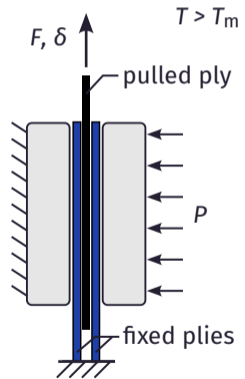
Experimental characterization

- Pull-through friction experiments at constant temperature, normal pressure, and sliding rate
- Apparent shear stress is calculated as:

$$\tau(t) = \frac{F(t)}{2A},$$

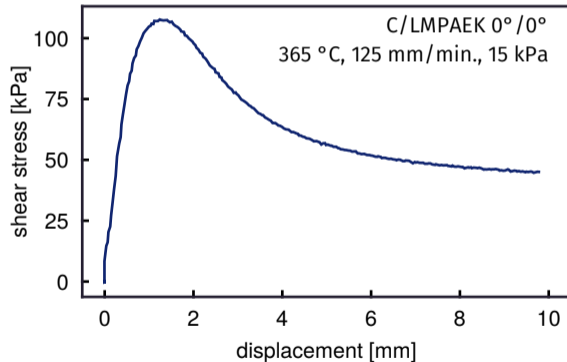
with A the tool surface area

- Literature reports the shear stress evolution or the derived coefficients of friction



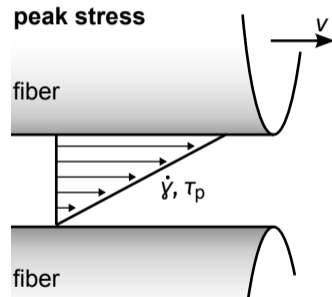
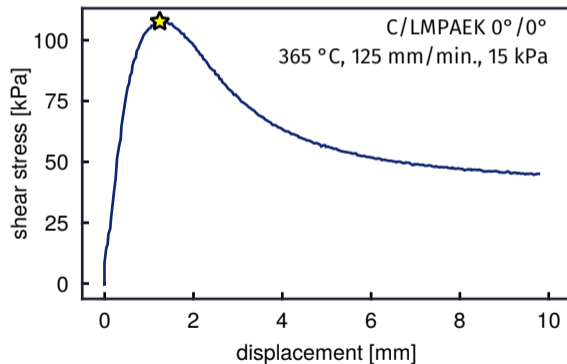
Ply-ply friction

Peak stress followed by a steady-state



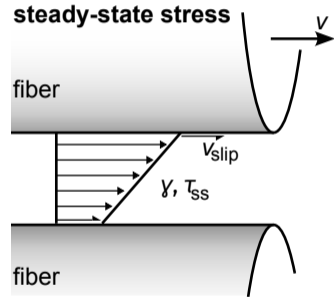
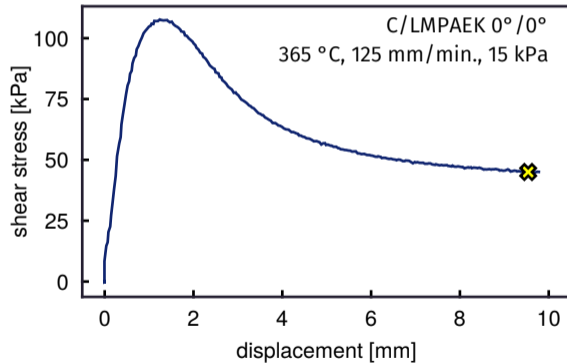
Ply-ply friction

Peak stress followed by a steady-state



Ply-ply friction

Peak stress followed by a steady-state



Ply friction in forming simulations

State-of-the-art

- Rate and pressure dependent **isotropic** friction models
- **Isothermal** and **isobaric** characterization, mostly above melt temperature at relatively high pressures
- Transition from peak and steady-state not captured, i.e., **no path dependence**
- **Long slip-distances**, especially compared to actual forming
- Characterization in fiber direction, limited **off-axis** data

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Today's presentation addresses the **orientation** dependence of slippage

Objective and approach

Objective

To analyze and quantify the orientation dependence of ply-ply and tool-ply friction of unidirectional carbon reinforced PAEKs

Objective and approach

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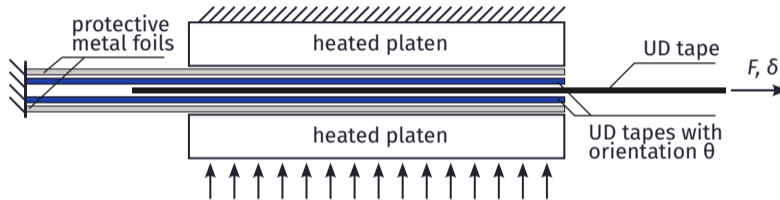
To analyze and quantify the orientation dependence of ply-ply and tool-ply friction of unidirectional carbon reinforced PAEKs

Approach:

1. Mature testing methodology using a newly developed pull-through friction tester
2. Perform ply-ply and tool-ply friction measurements for C/LMPAEK
3. Analyze data and compare to (preferably simple) mechanistic models

Experimental work

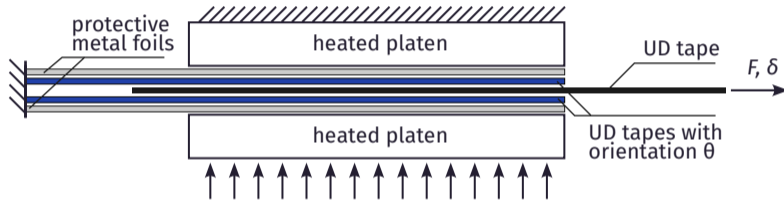
Materials and methods



- Toray AC TC1225 C/LMPAEK at 365 °C
- Pull-through setup with fixed outer plies at orientation θ

Experimental work

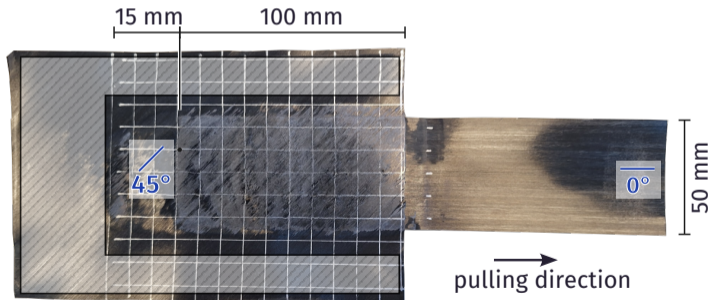
Materials and methods



- Toray AC TC1225 C/LMPAEK at 365 °C
- Pull-through setup with fixed outer plies at orientation θ
- Pulled ply was either a UD tape oriented at 0°, or a metal foil (with and without Marbocote release agent) to represent a tool surface

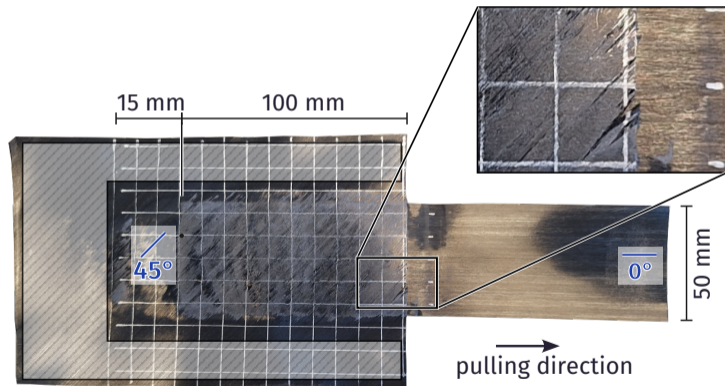
Specimen

Clamping and specimen design



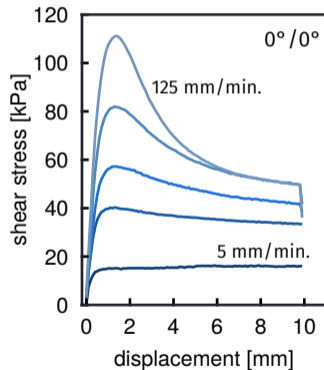
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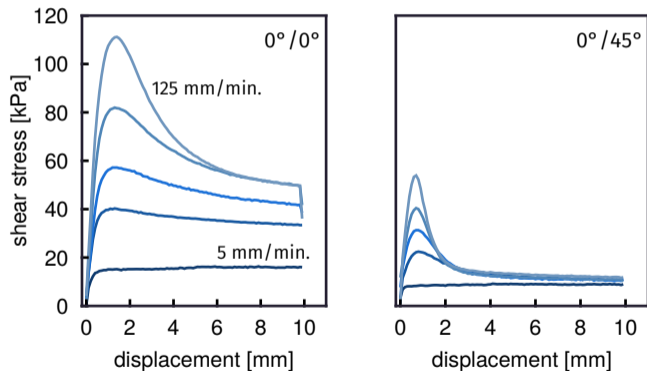
Ply-ply friction

Effect of rate for different ply orientation



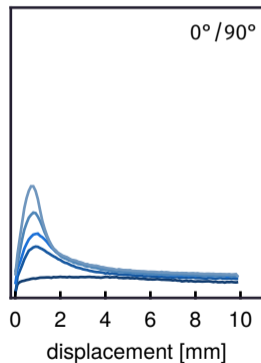
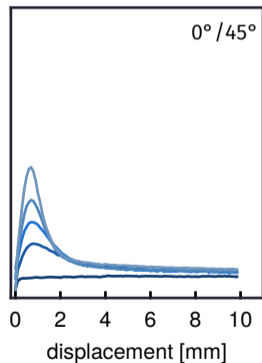
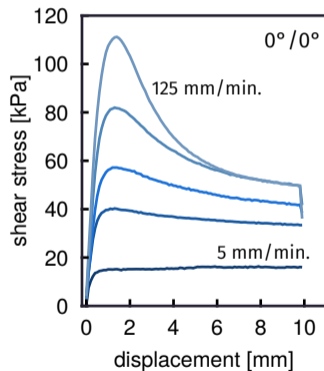
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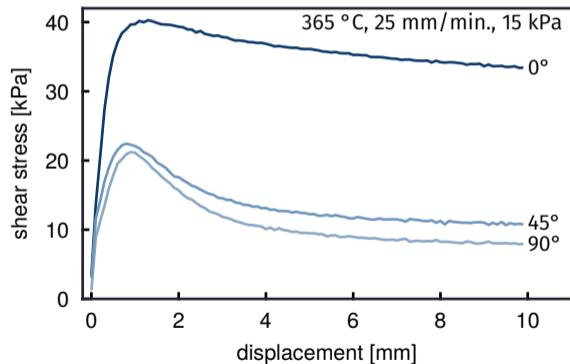
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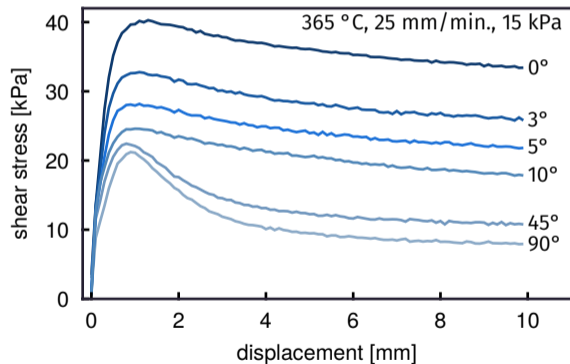
Ply-ply friction

Effect of ply orientation at fixed rate



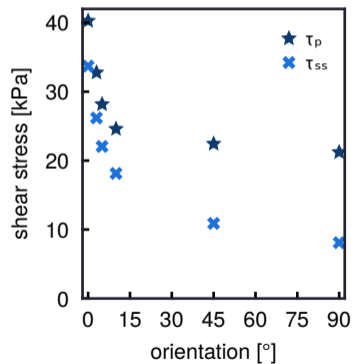
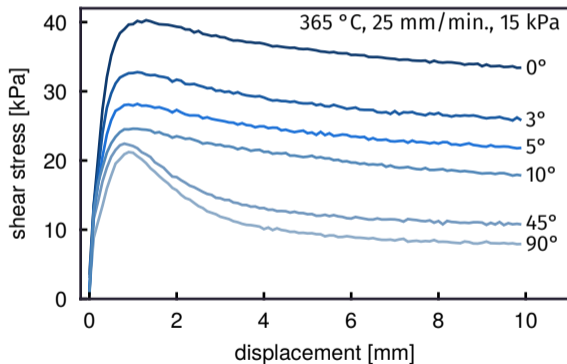
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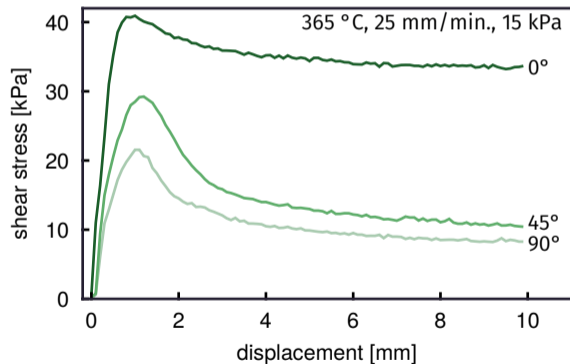
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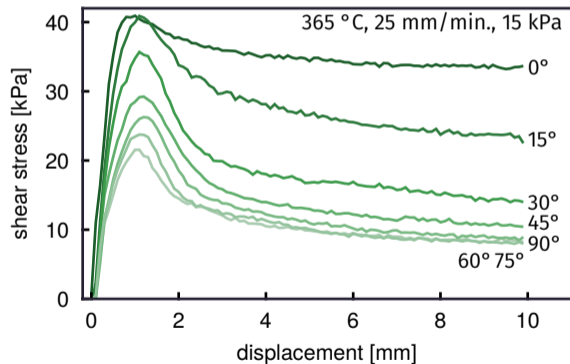
Tool-ply friction

Effect of ply orientation at fixed rate



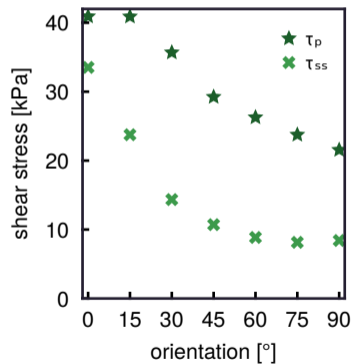
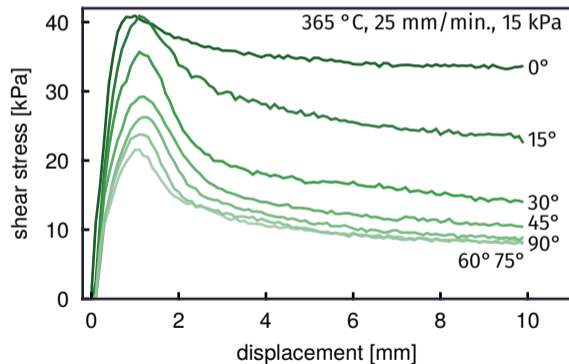
Tool-ply friction

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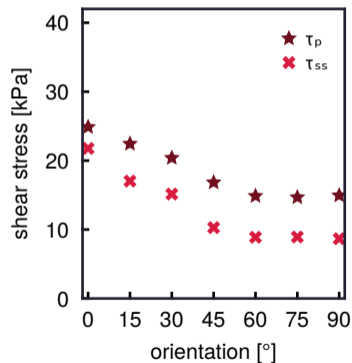
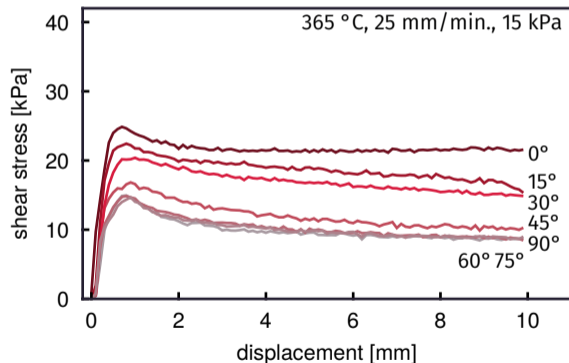
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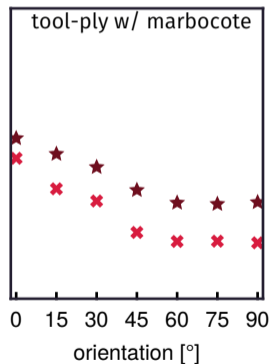
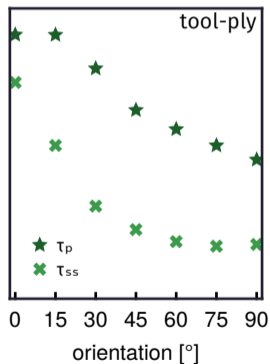
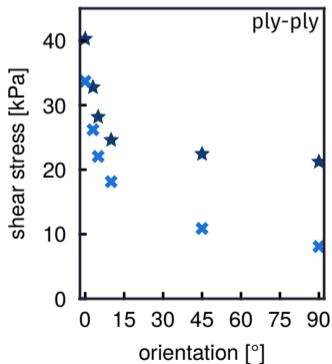
Tool-ply friction with release agent

Effect of ply orientation at fixed rate



Overview

Effect of ply orientation at 25 mm/min



Main findings

Overview

- Ply **clamping** critical to minimize fiber deformation during testing

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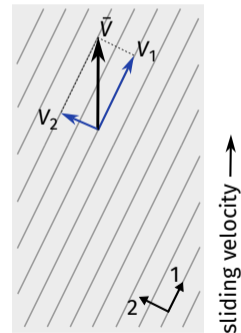
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Next, we move to develop a (simple) **empirical model** that can describe the orientation dependence

Linear orthotropic friction model

Empirical modeling

Assuming orthotropic friction in the fiber frame
(1–2) with linear rate scaling:



Linear orthotropic friction model

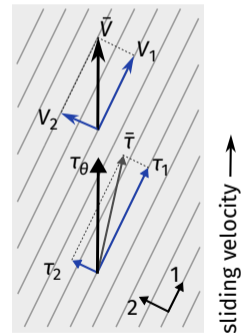
Empirical modeling

Assuming orthotropic friction in the fiber frame
(1–2) with linear rate scaling:

$$\tau_1 = \tau_1^{\text{ref}} \frac{V}{V_{\text{ref}}} \cos \theta, \quad \tau_2 = \tau_2^{\text{ref}} \frac{V}{V_{\text{ref}}} \sin \theta,$$

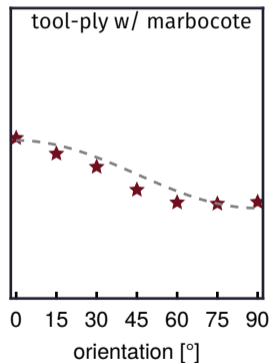
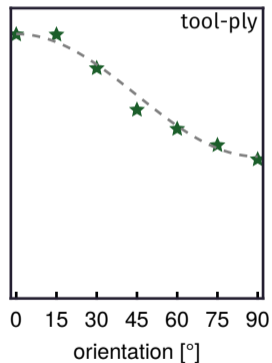
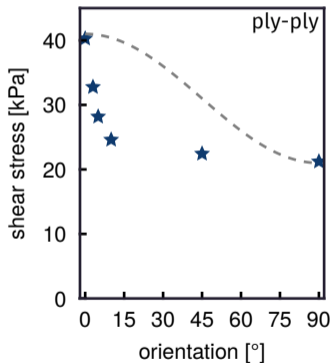
which gives the shear stress in sliding direction:

$$\tau_\theta = \frac{V}{V_{\text{ref}}} \underbrace{\left(\tau_1^{\text{ref}} \cos^2 \theta + \tau_2^{\text{ref}} \sin^2 \theta \right)}_{\text{orientation dependence}}$$



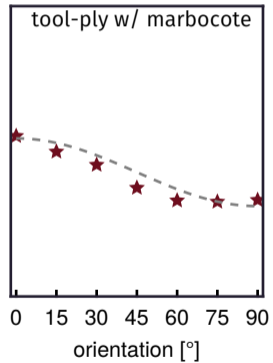
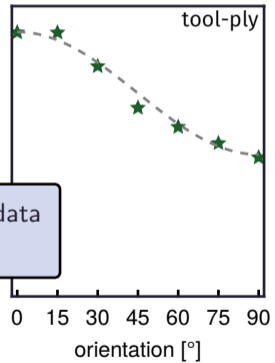
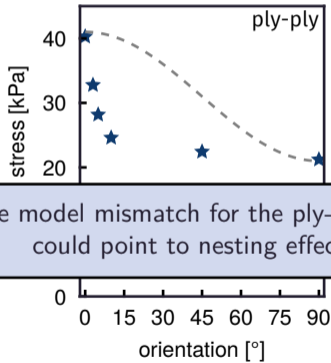
Fitted results

Empirical modeling



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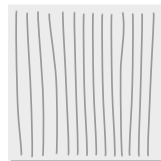
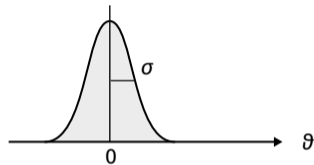
The model mismatch for the ply-ply data could point to nesting effects

Probabilistic nesting model

Empirical modeling

Local fiber orientations in the two contacting plies:

$$\vartheta_0 \sim \mathcal{N}(0, \sigma^2), \quad \vartheta_\theta \sim \mathcal{N}(\theta, \sigma^2)$$

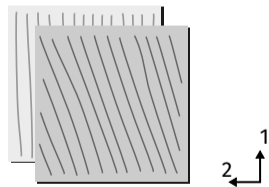
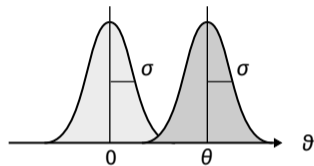


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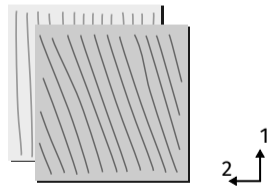
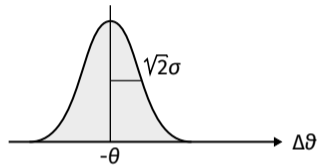
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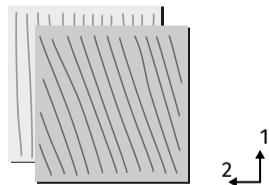
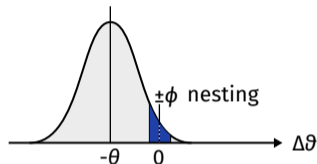
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Nested area fraction for critical nesting angle ϕ :

$$A_n = \Pr(|\Delta\vartheta| < \phi) = \Phi\left(\frac{\phi + \theta}{\sqrt{2}\sigma}\right) - \Phi\left(\frac{\theta - \phi}{\sqrt{2}\sigma}\right)$$



Probabilistic nesting model

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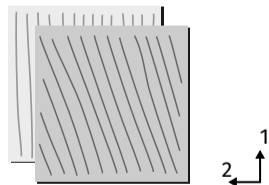
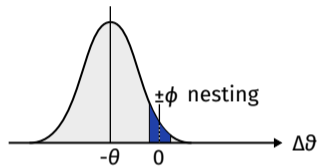
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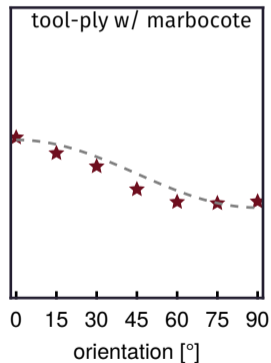
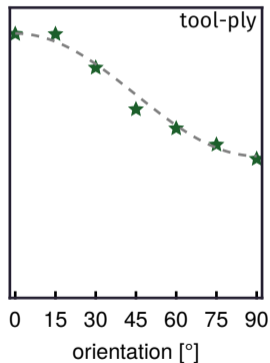
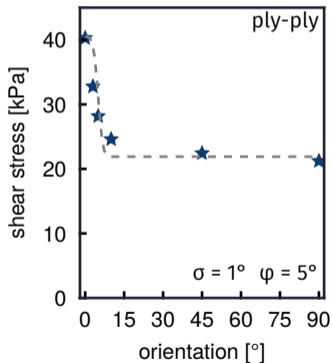
Resulting shear stress:

$$\tau = \tau_{\parallel} A_n + \tau_{\perp} (1 - A_n)$$



Empirical model

Fitting of peak stress



Conclusions & recommendations

What have we learned:

- Ply–ply and tool–ply friction show strong fiber orientation dependence
- Ply–ply friction decreases more rapidly with misalignment than tool–ply friction
- A release agent significantly reduces both peak and steady-state friction

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What's next:

- Extend the dataset to include a wider range of sliding rates and normal pressures
- Develop **micro-mechanical models** for orientation-dependent friction
- Implement orientation-dependent friction laws in **forming simulations**

Thank you!

Sheffield, UK, June 30th, 2026

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