An In-situ Peel Test for Characterizing Prepreg Tack as Applied to Automated Fiber Placement

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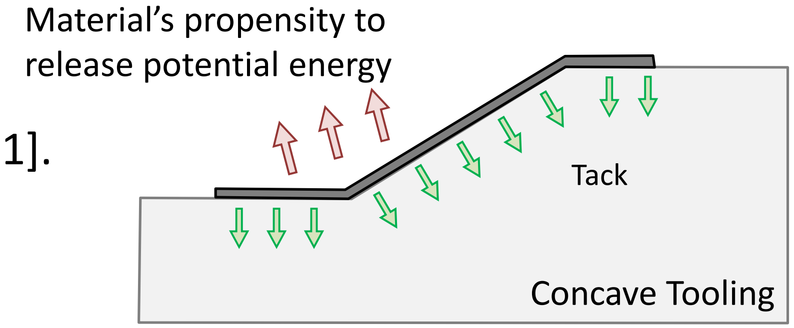
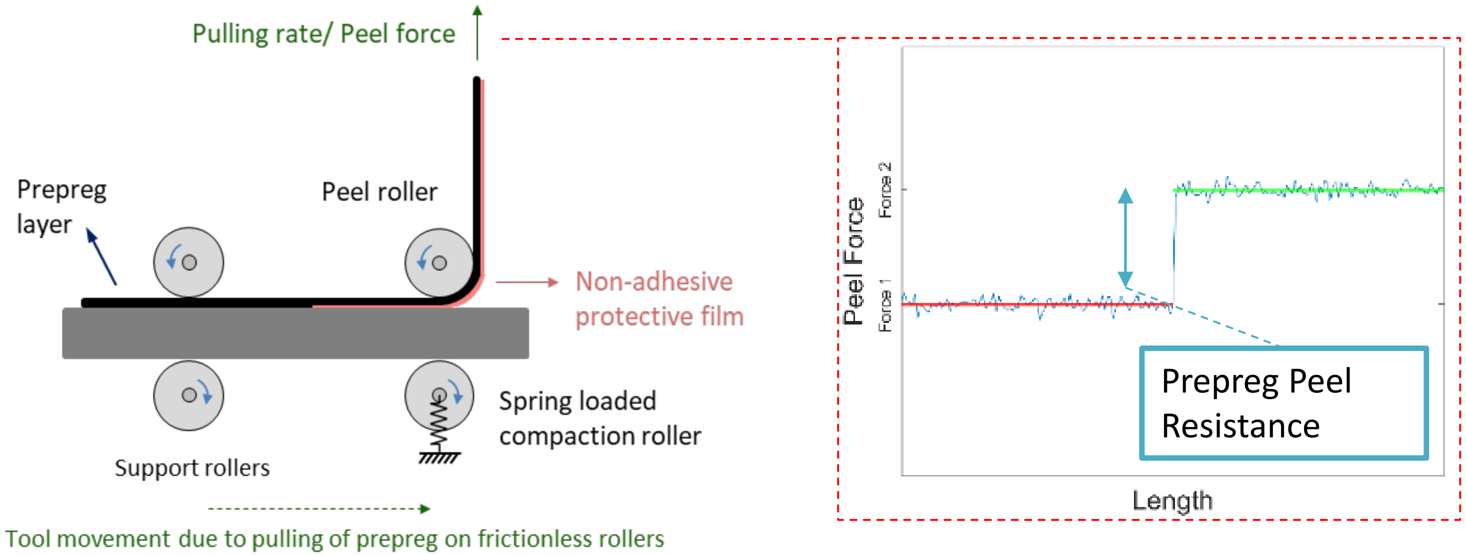
Project Background

- This presentation is based on research performed in a project funded by the US Air Force Office of Scientific Research under the guidance of Dr. John Russell, Chief, Structures Technology Branch, Air Force Research Laboratory, entitled 'Science Based Automation of Composites Manufacturing'
- Project focuses on the fusion of physics-based simulation and data science for automating composites manufacturing, using a process- and material-centric sense-think-act framework

Prepreg Tack

- Tack is the primary mechanism that resists defect formation in AFP processing.
- Current Gold Standard for measurement of prepreg tack is ASTM 8336-21 [1].
  - A continuous application and peel method
  - Specimen is consolidated (tack cohesion is developed) and peeled in a single stage under a 'peel roller'





[1] Endruweit, Andreas, et al. "Characterisation of tack for uni-directional prepreg tape employing a continuous application-and-peel test method." *Composites Part A: Applied Science and Manufacturing* 114 (2018): 295-306.

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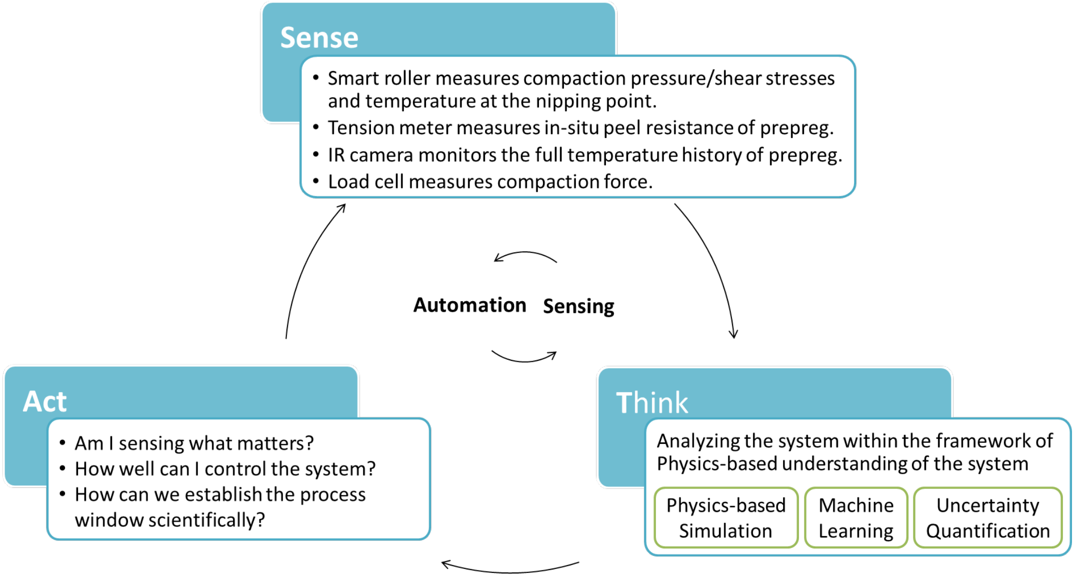
Science Based Automation of Composites: µAFP

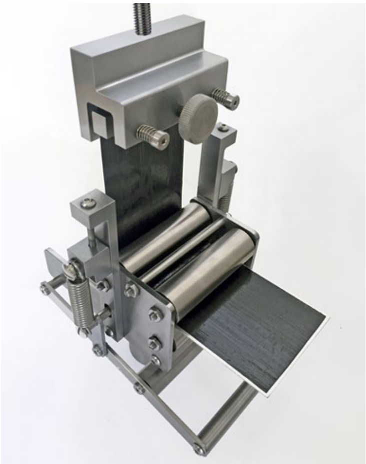
- Are we sensing what really matters in the process?
- How can we establish processing windows scientifically?



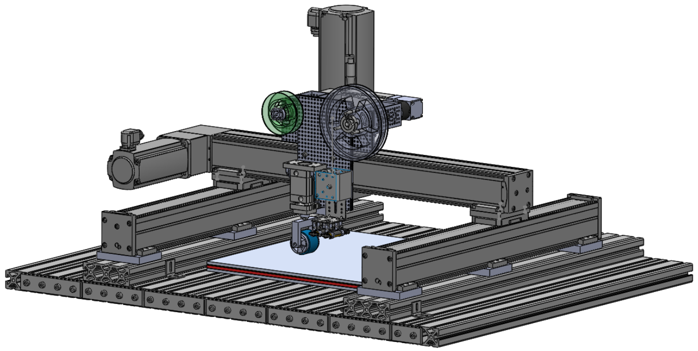
AFP: Characterization to Manufacturing

Probe Test

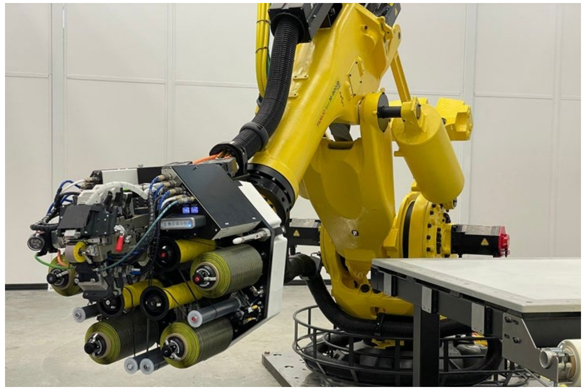
Continuous Application and Peel (ASTM 8336-21)



µAFP



Research AFP



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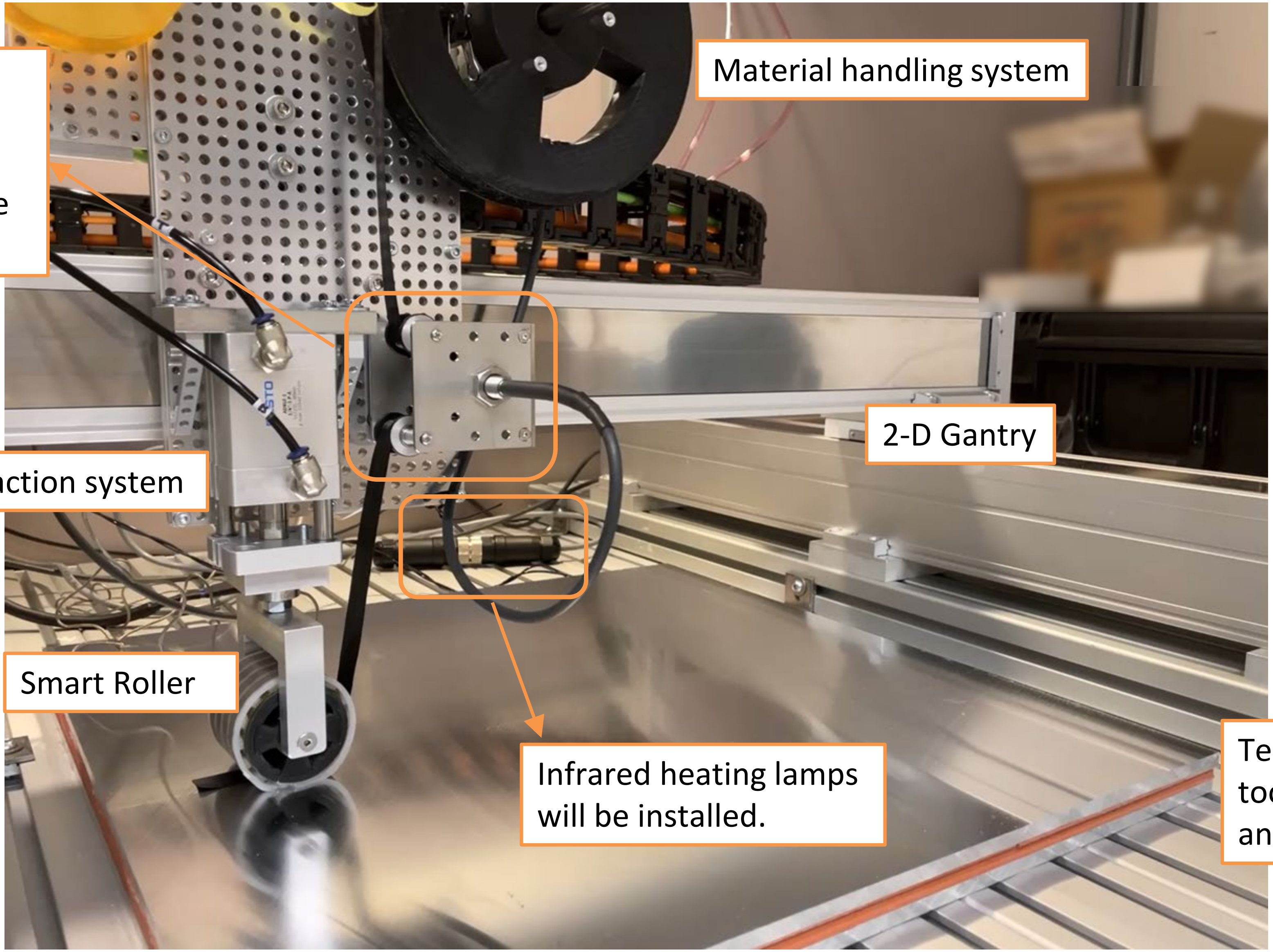
Development and Implementation of the µAFP



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Overview of AFP Smart Rollers

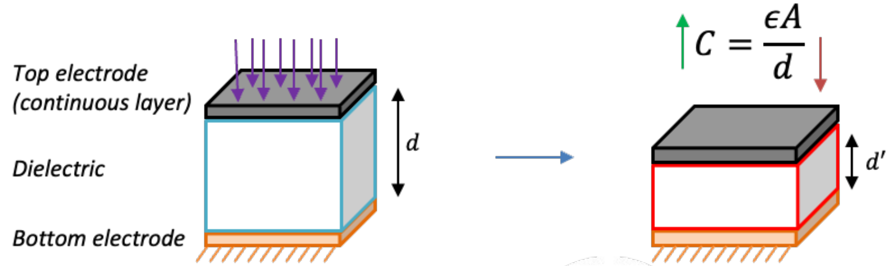
A **fully wireless smart roller** featuring pressure sensitivity, Bluetooth communication, and a battery onboard, is installed in the AFP simulator.

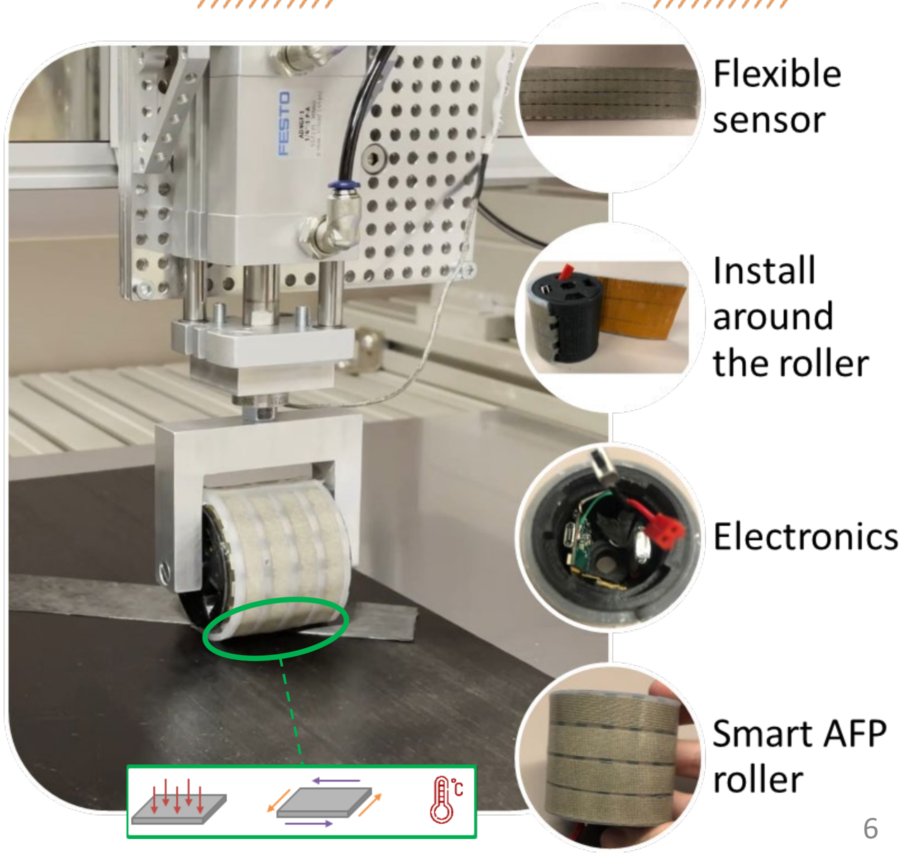
The smart roller measures *local nip point* pressure and shear stresses, in-situ. Temperature sensing capability will be added in future.

Example: substrate feature detection

The diagonal pattern of the substrate is detected between rows 9 and 2.

Working principle of pressure-sensing taxels (each sensing point – tactile pixel):





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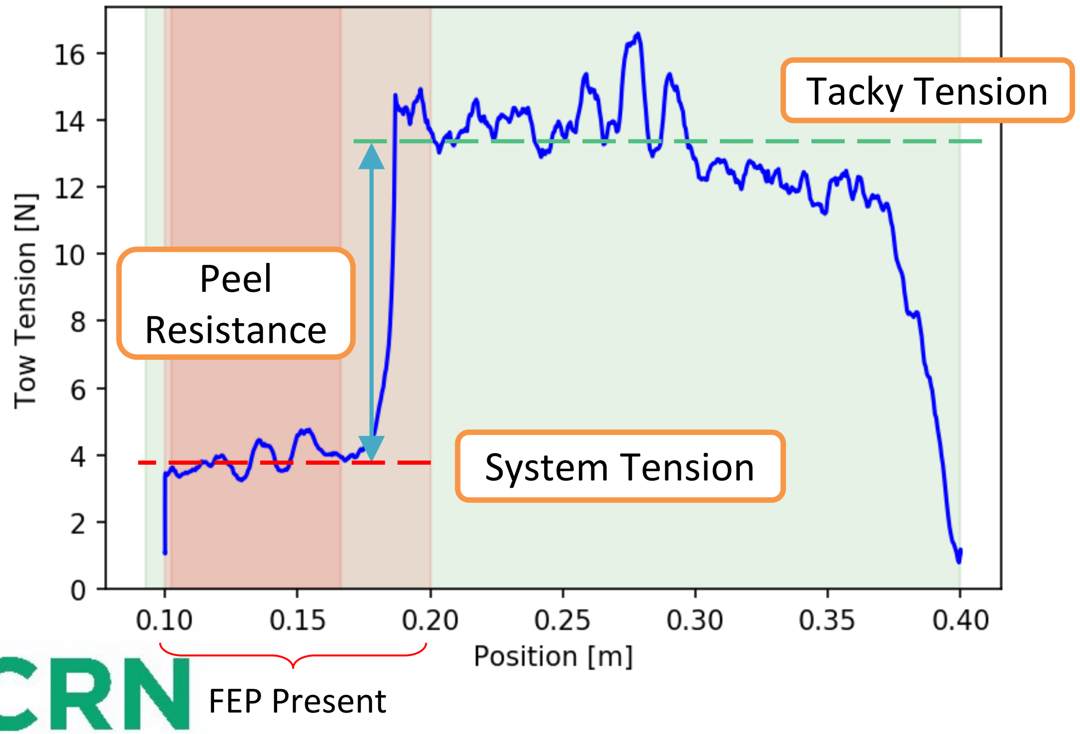
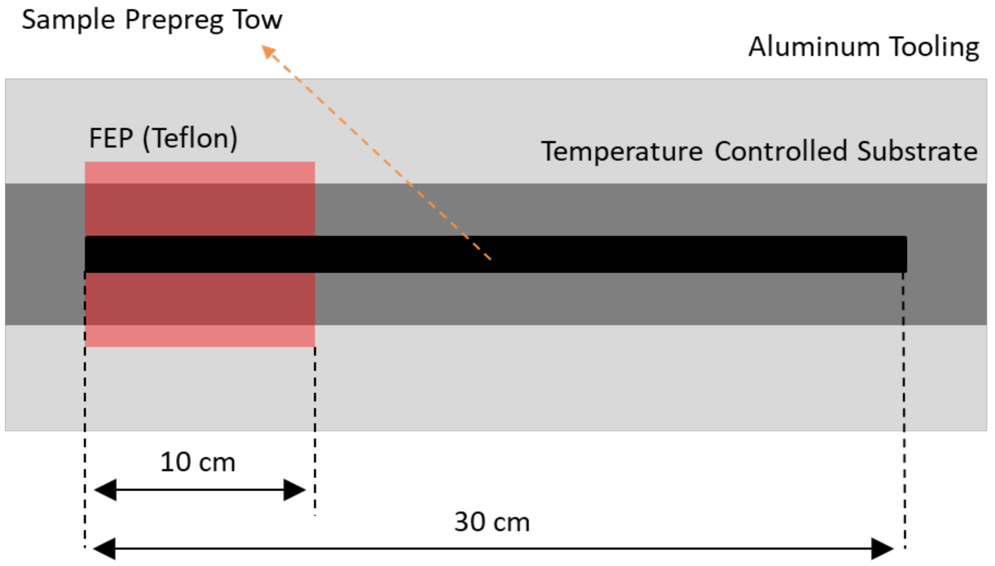
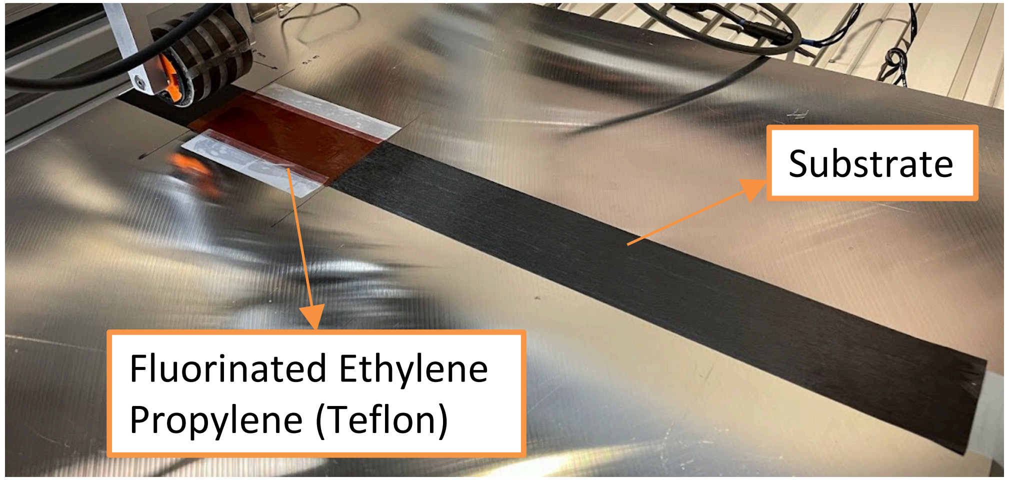
Typical In-situ Peel Test Setup and Results

- **In-situ Peel Test Method:** deposit prepreg tows simulating AFP conditions, then reverse motion and continue to peel the tow off from the substrate.
- **Material System Used:** Non-AFP high tack AS4/8552 Prepreg
- **Material Preparation:** 1/2"– wide 'tows' are cut from broad prepreg material

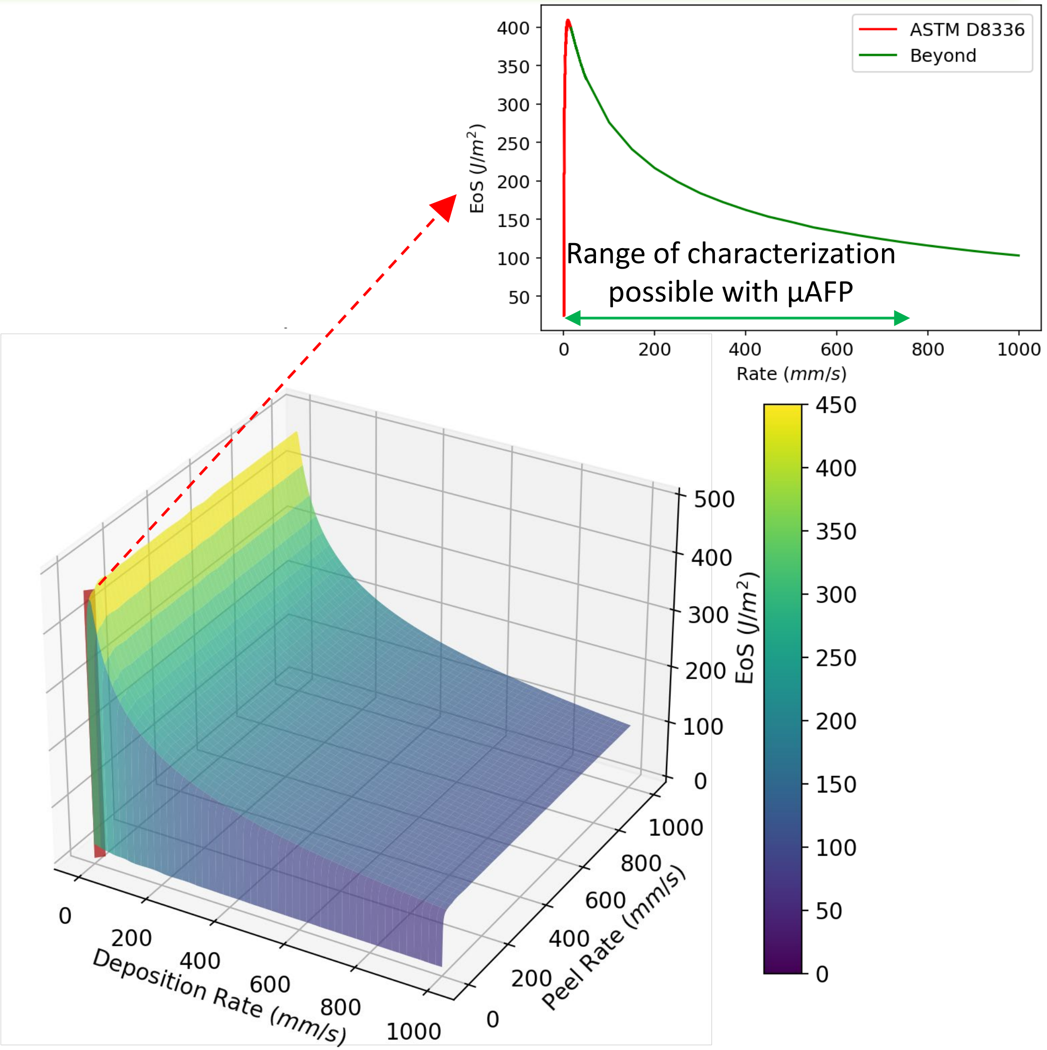






Prepreg Tack: Literature and Positioning

- Current Gold Standard: ASTM 8336-21
- Tack Master Curves are built using the ASTM Standard Method
  - Tests are typically performed between 0.1-17 mm/s (limited by UTM capabilities)
  - Time Temperature Superposition principle is used to extrapolate to rates relevant to AFP
- Unique Features of the µAFP:
  - Deposit and peel at up to **700 mm/s**
  - Uncoupled and **independent** control of deposition and peel rates, e.g.
  - Characterize tack at ‘**natural’ peel rates** for realistic deposition rates
  - Implement and evaluate new sensor technologies, e.g. smart roller
  - **Future** extension to steered tow, …



Range of characterization possible through ASTM D8336 shown on results of the open 8552 tack model at a constant temperature

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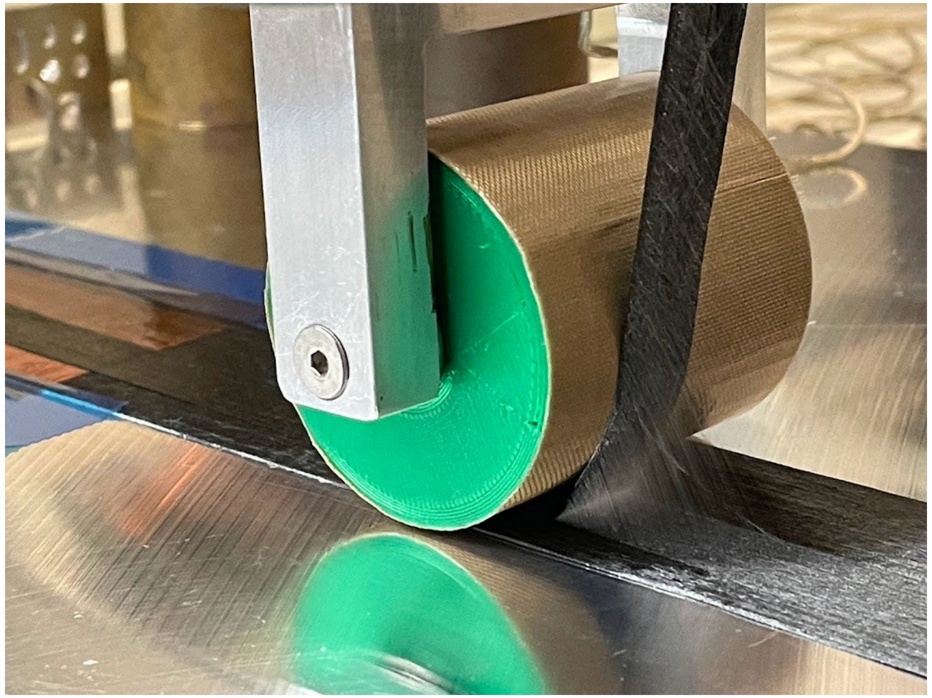
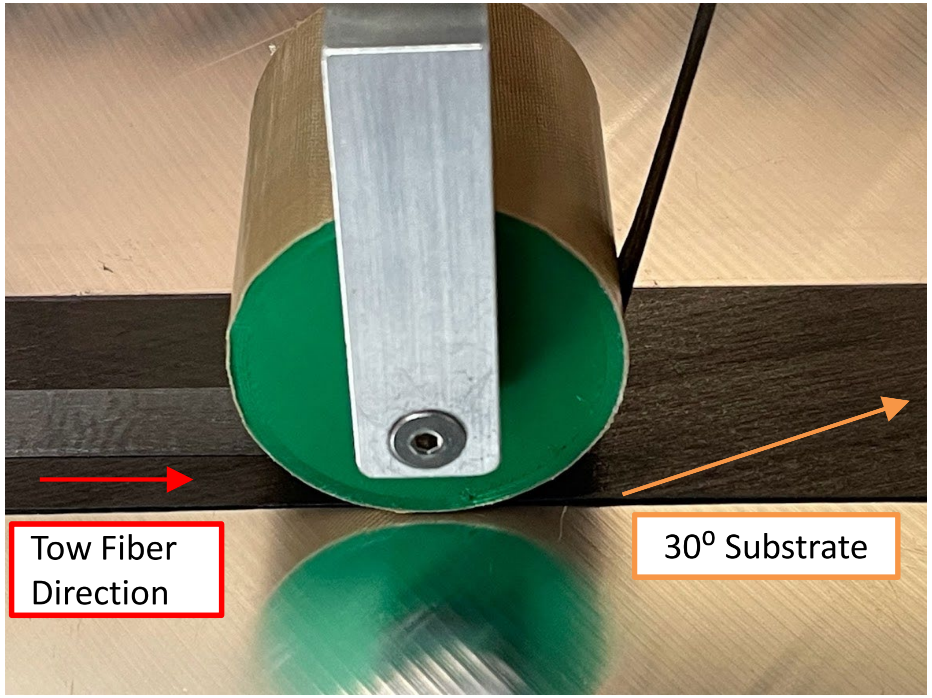
Overview of In-situ Tack Studies

Three Tack Studies are Presented:

- Constant deposition and peel rate (replicating the ASTM Standard conditions) and method validation
- Effect of varying deposition and peel rates independently
- Effect of substrate orientation on the development of tack



Fibril formation during cohesive failure



Studying the effect of substrate fiber orientation

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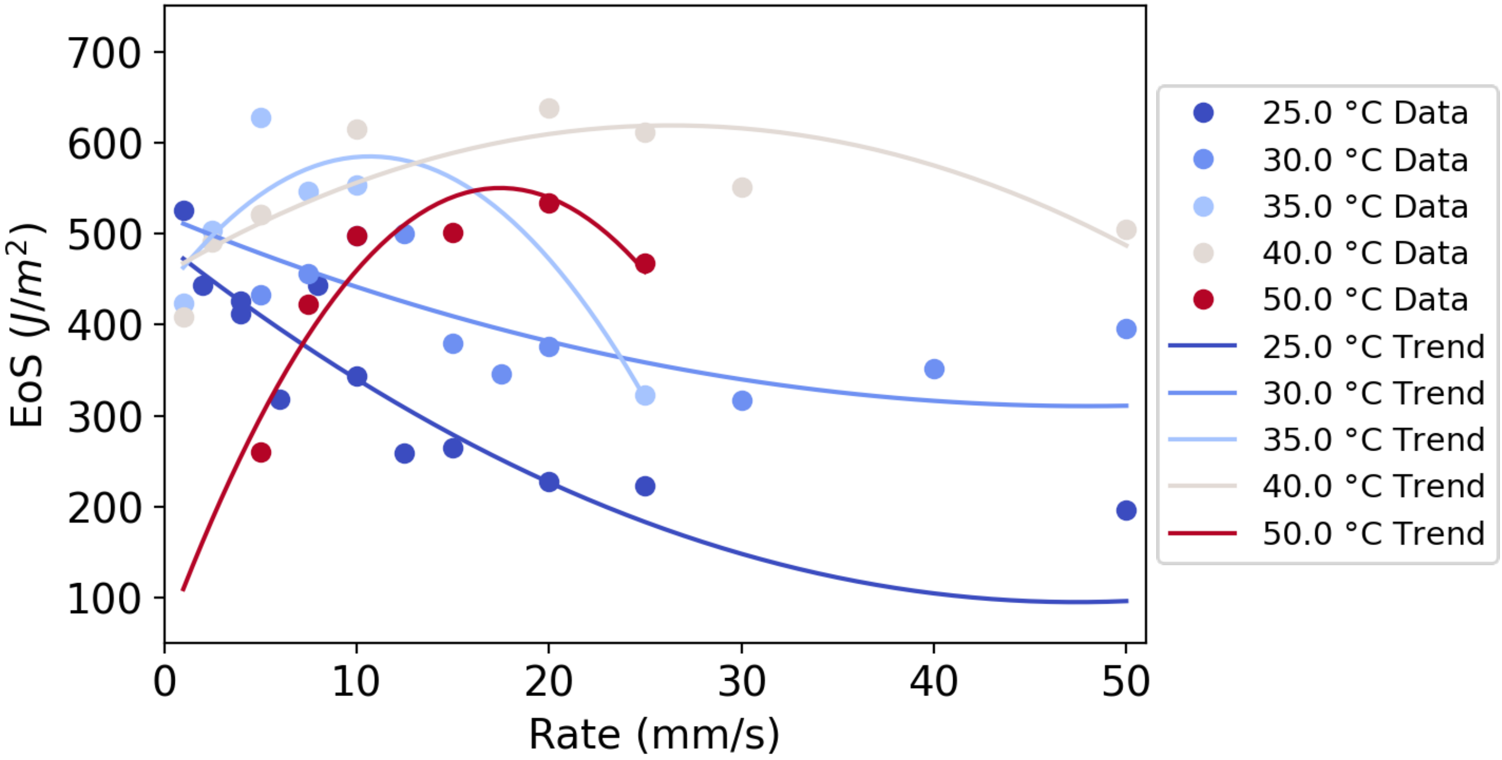
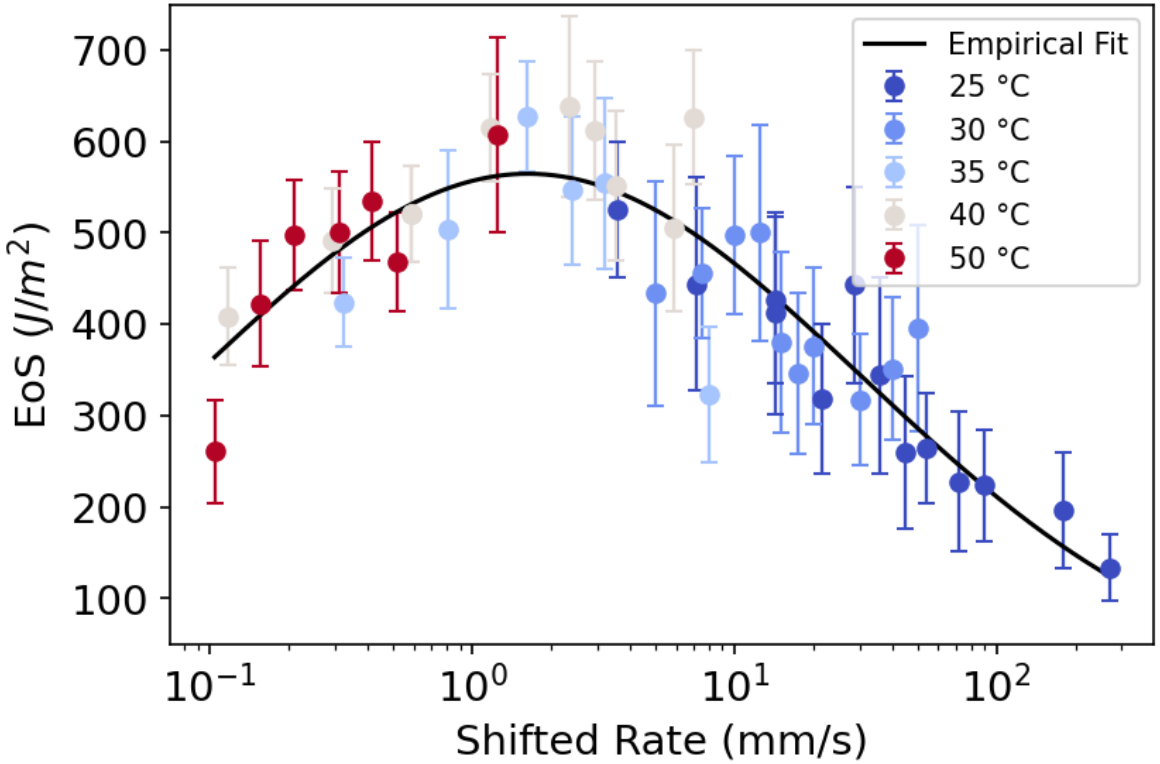
Equal Deposition and Peel Rate Studies

- A first series of tests have been performed with equal deposition and peel rates to replicate the ASTM test conditions.
- Equal deposition/peel rate studies are conducted to construct the tack master curve.
- In-situ peel procedure is performed at 25, 30, 35, 40, and 50 °C using the μAFP.



Constructing the Tack Master Curve Using the Open 8552 Model Shift Factors

- A physics-based tack model was developed under the NASA ACP program [2].
- This is an open-literature calibration of the ACP tack model for the 8552 resin system, wherein the model parameters were calibrated based on probe test data obtained at low rates (<1 mm/min).
- Shift factors of the open-literature tack model are used to shift our experimental results to construct the tack master curve.
- Successful construction of the Gaussian-shaped master curve confirms the validity of the in-situ peel method as performed by the µAFP system.



[2] Forghani, A., Hickmott, C., Houman, B., Wohl, C., Grimsley, B., Coxon, B., & Poursartip, A. (2017). A Physics-Based Modelling Framework for Simulation of Prepreg Tack in AFP Process. In *SAMPE Technical Conference* (pp. 22-25).

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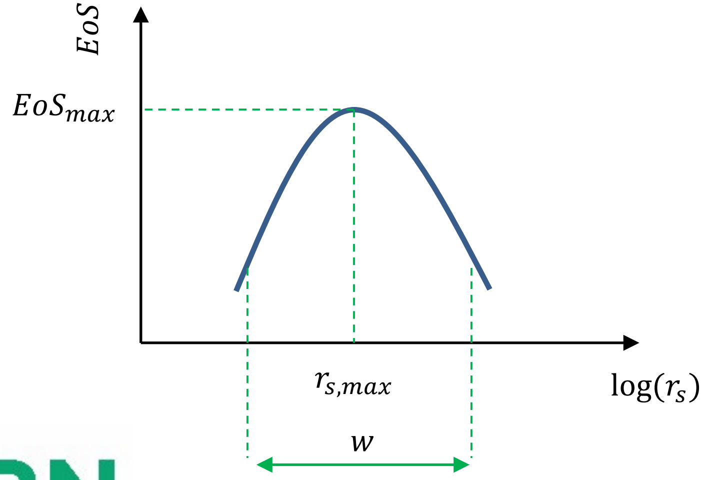
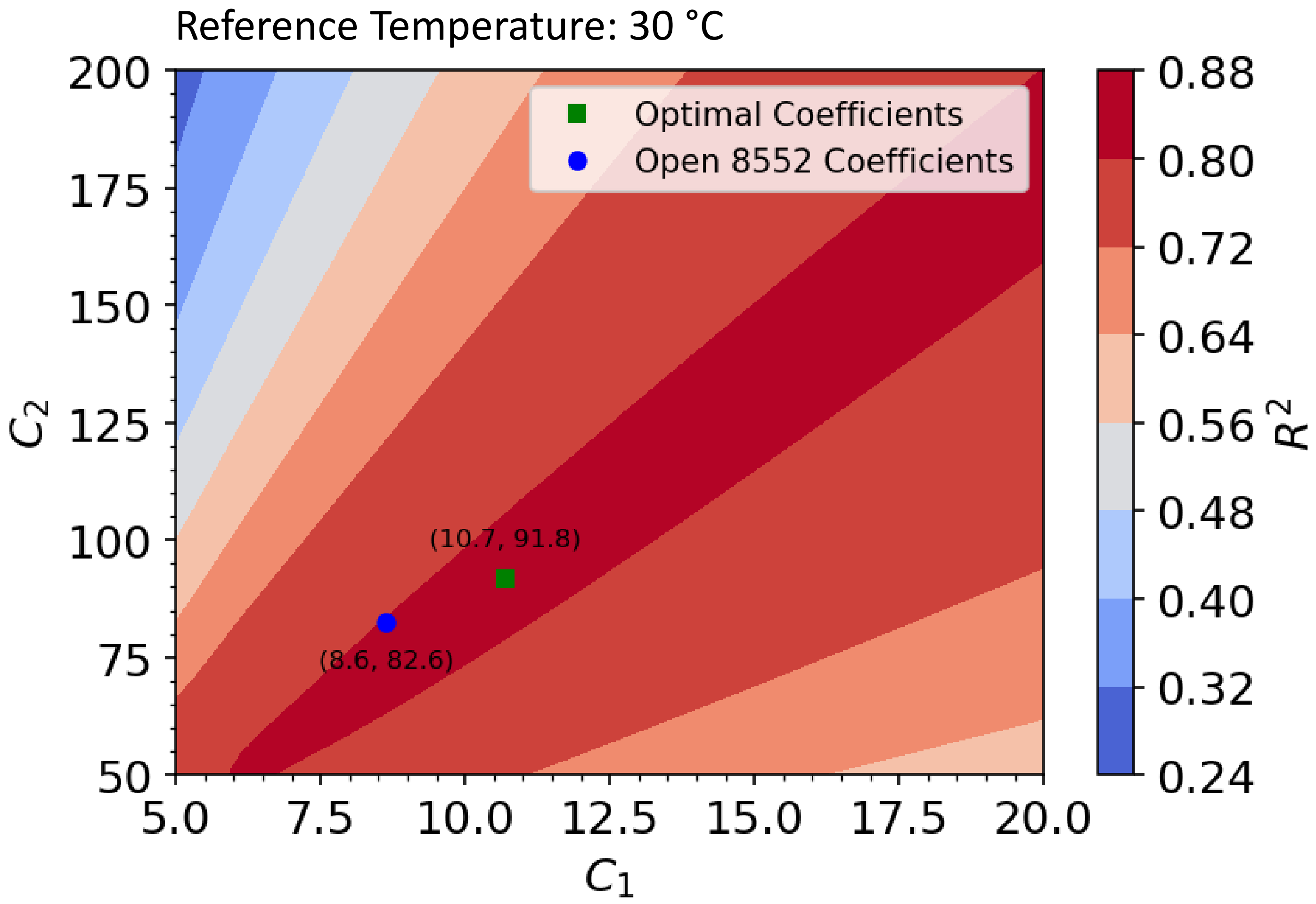
Optimal Application of Time Temperature Superposition

Assuming the tack master curves take the form of a Gaussian curve [1], we iterate over a reasonable range of William-Landel-Ferry C1, C2 parameters (for a given Reference Temperature) to find the optimal set of (C1, C2) that best construct the shape of the master curve:

$$EoS = EoS_{max} \exp\left(-\left(\frac{\log_{10} r_s - \log_{10} r_{s,max}}{w}\right)^2\right)$$

The best fit has the highest R^2 of fit to experimental data.





Both sets of coefficients are in the high-quality band.

[1] Endruweit, Andreas, et al. "Characterisation of tack for uni-directional prepreg tape employing a continuous application-and-peel test method." *Composites Part A: Applied Science and Manufacturing* 114 (2018): 295-306.

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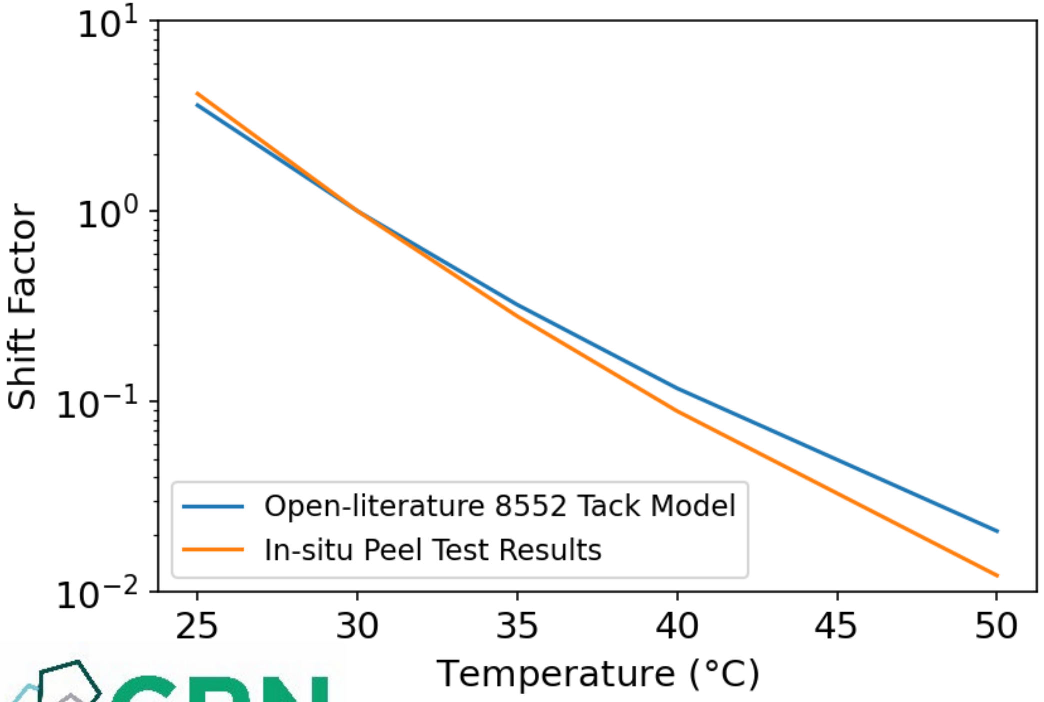
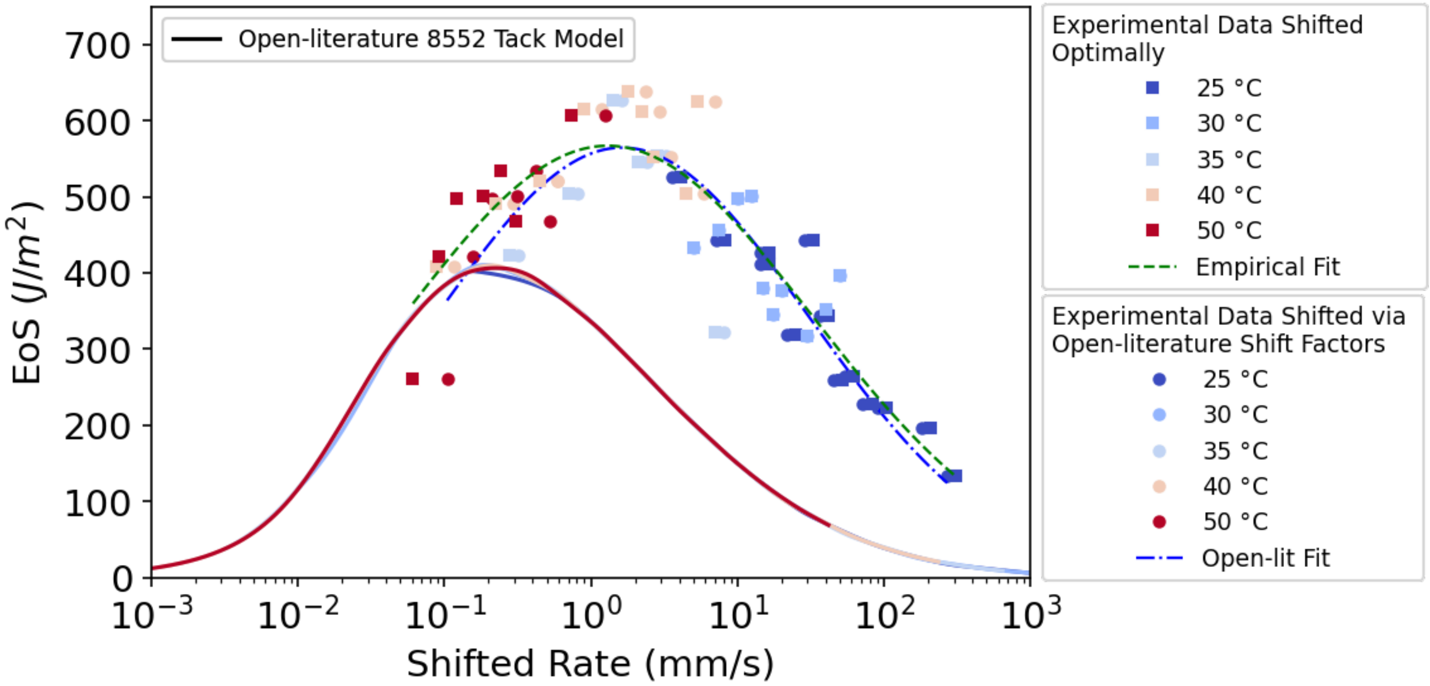
Optimal Tack Master Curve at T_{ref} = 30 °C

- Having the set of WLF parameters that optimally shift our experimental data, we can compare the optimal tack master curve with the master curve shifted using the open 8552 model coefficients.
- Experimental data are compared with predictions from the open-literature 8552 calibration of the tack model.
- Open 8552 tack mode: calibrated (CMT-US) based on probe tests (NASA) at low rates (<1 mm/min).
- Both sets of shift factors shift the experimental data effectively, but there are discrepancies in max. tack and max. rate at which max tack occurs between experiments and model predictions.

Comparison of Shift Factors



Comparison of Shifted Experimental Results



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Effect of Deposition Rate on Tack

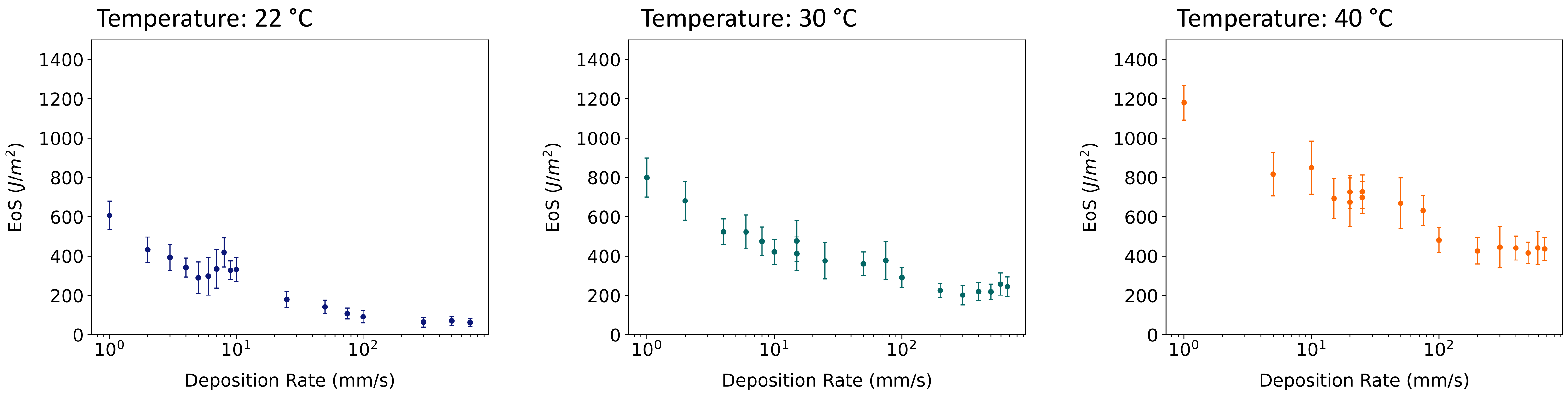
Having shown that our data behaves comparably to the current best practice, we now exercise the unique features of the µAFP. Here, deposition rate is varied independently from the peel rate to isolate its effect on tack development.

Test Conditions:

- Peel Rate: 50 mm/s constant in all tests
- Temperatures: 22, 30, 50 °C
- Rigid Roller
- 0° Prepreg Substrate (substrate and tow fibers are parallel)

Takeaways:

- Energy of Separation drops with increasing deposition rate as a result of decreasing Degree of Intimate Contact achieved between tows and substrates.



Effect of Peel Rate on Tack

Next, peel rate is varied independently from the deposition rate to isolate its effect on tack resistance.

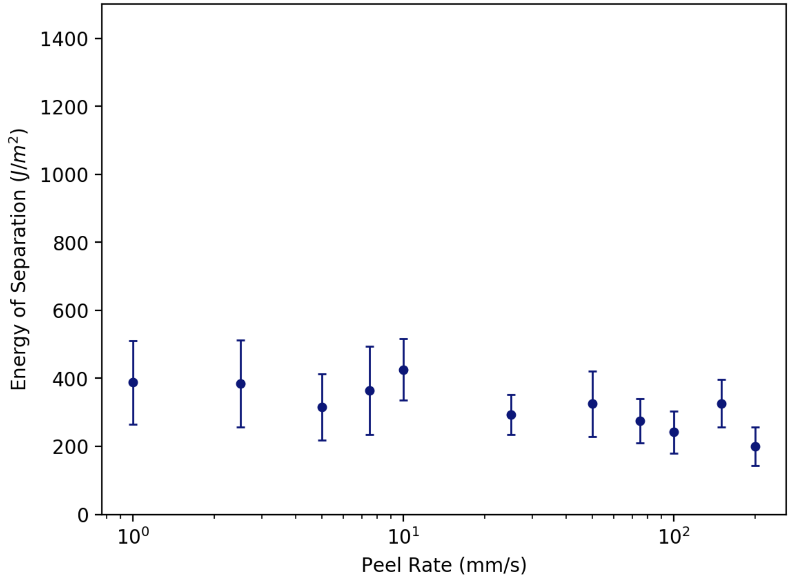
Test Conditions:

- Deposition Rate: 10 mm/s constant in all cases
- Temperatures: 22, 30, 50 °C
- Rigid Roller
- 0° Prepreg Substrate (substrate orientation parallel to tow deposition angle)

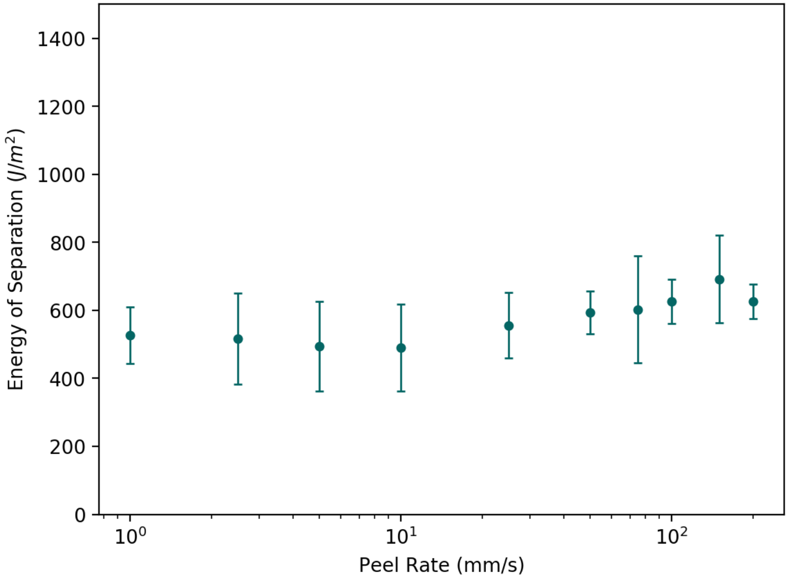
Takeaways:

- Two different mechanisms are observed.
- At 40 °C, where a high Degree of Intimate Contact is achieved as a result of lower resin viscosity, EoS increases with the increasing peel rate illustrating the rate dependent resin response.
- At lower temperatures where contact is incomplete, EoS decreases with increasing peel rate, at a constant deposition rate.

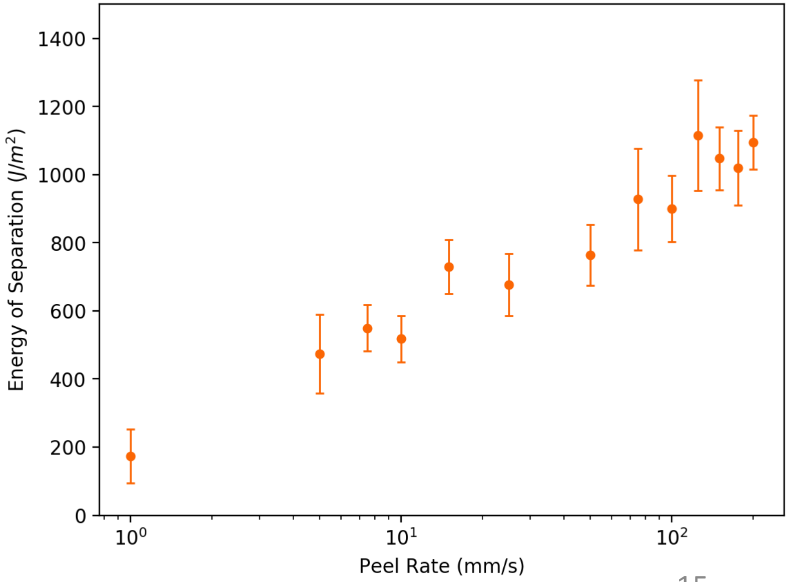
Temperature: 22 °C



Temperature: 30 °C



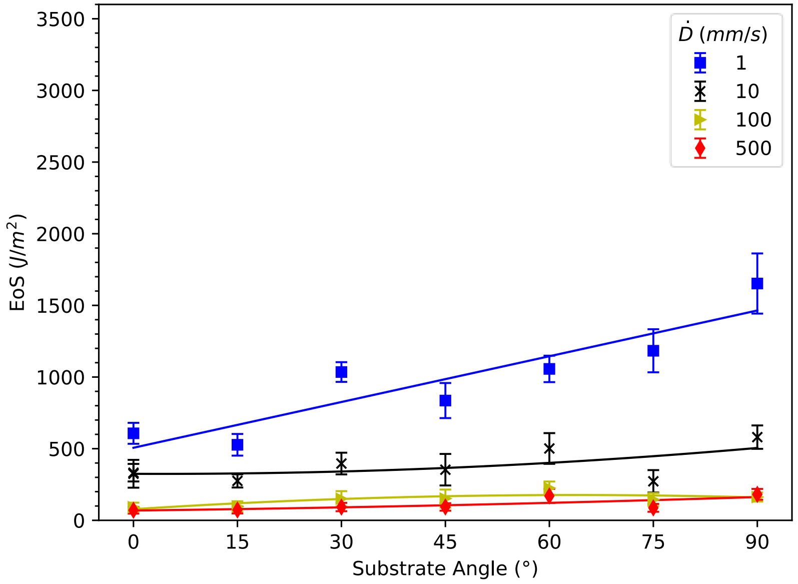
Temperature: 40 °C



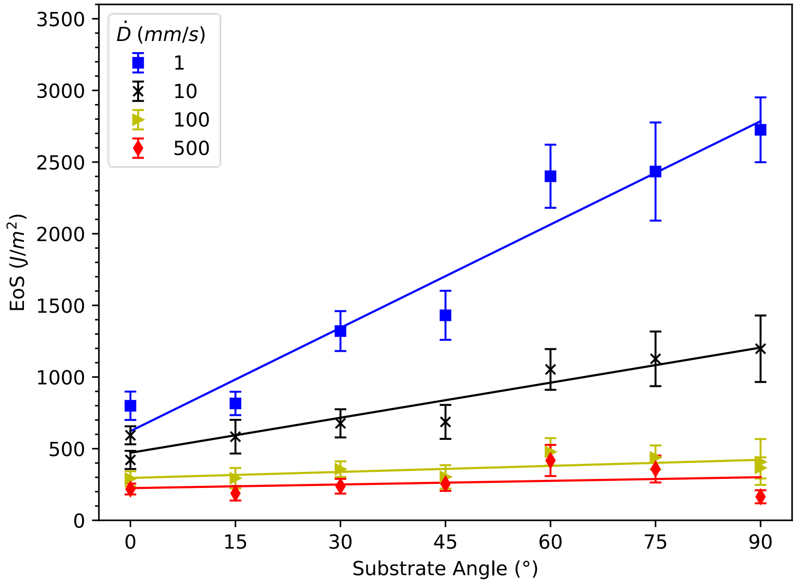
Angled Substrate: Varying Deposition Conditions

- Constant peel rate of 50 mm/s in all cases.
- Results for varying substrate angles are shown with respect to 0° tow.
- EoS generally ***increases*** with ***substrate angle*** under various deposition conditions

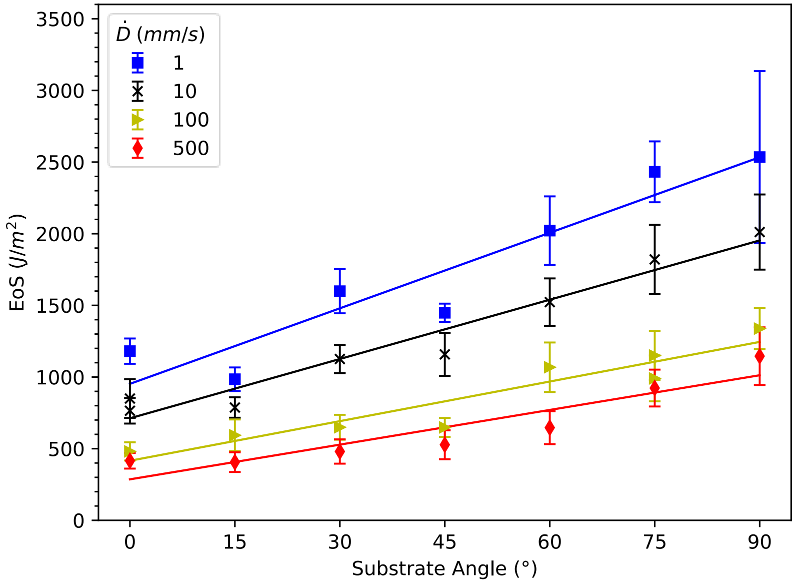
Temperature: 22 °C



Temperature: 30 °C



Temperature: 40 °C



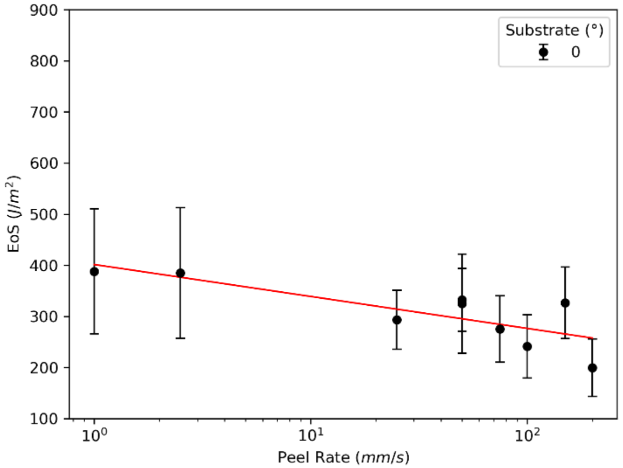
Angled Substrate: Varying Peel Conditions – Low DoIC

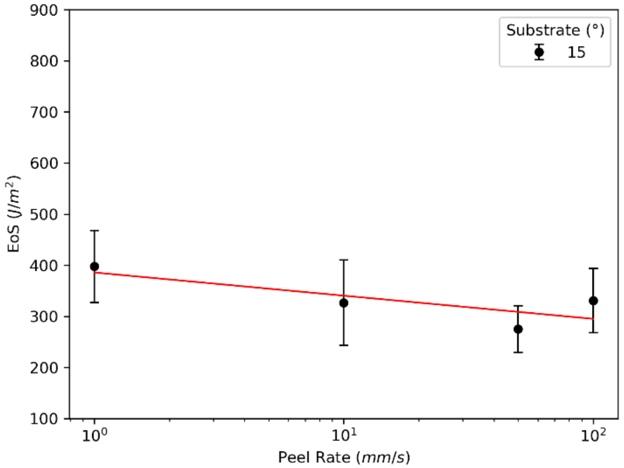
Low DoIC Condition:

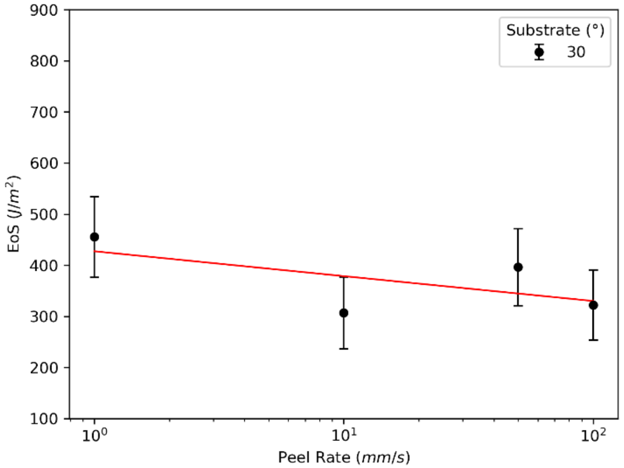
- Temperature: 22 °C
- Deposition Rate: 10 mm/s

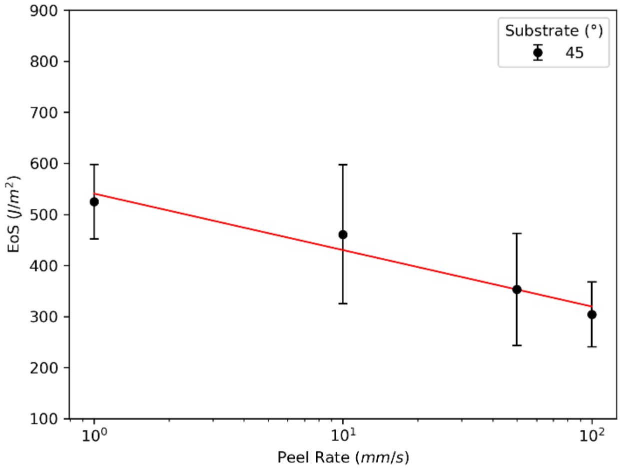
Results for varying substrate angles are shown with respect to 0° tow.

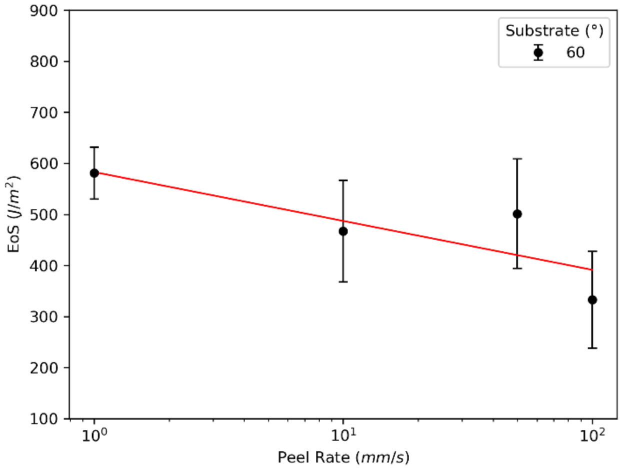
➢ EoS generally ***remains constant or decreases*** with increasing ***peel rate*** under conditions with a low Degree of Intimate Contact.

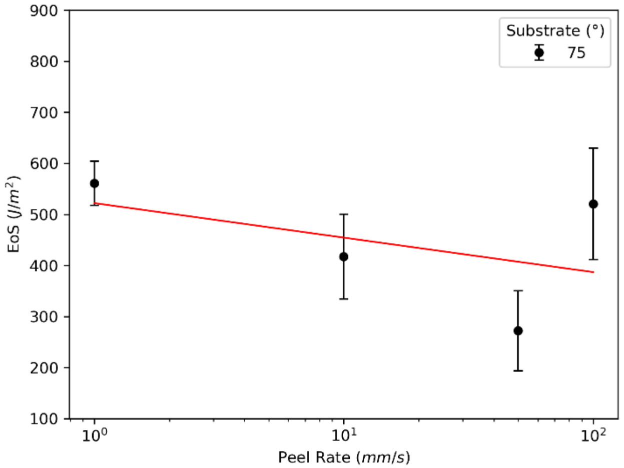


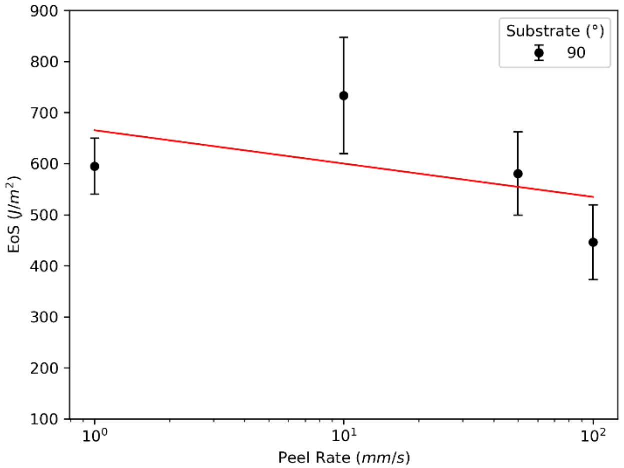












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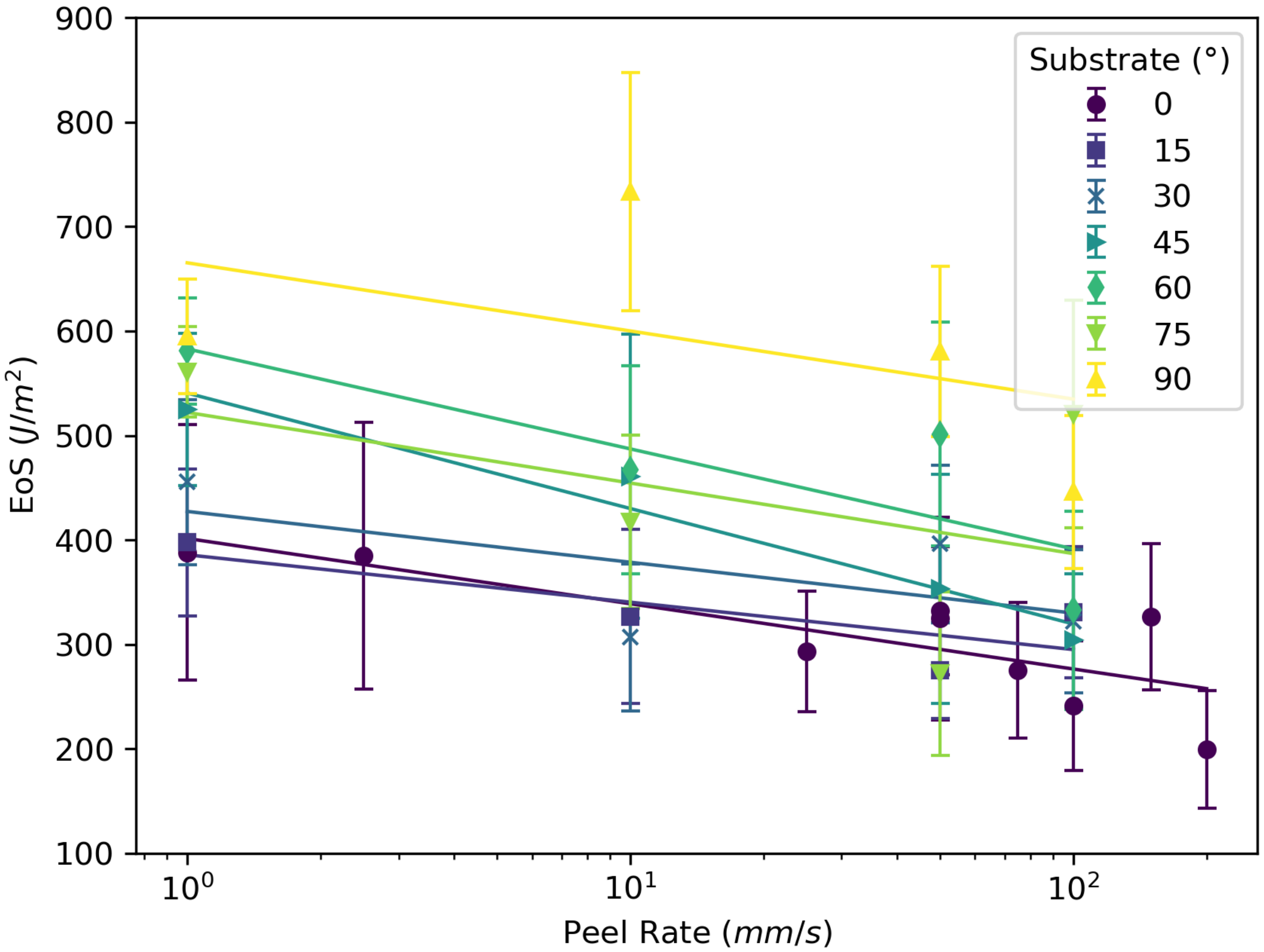
Angled Substrate: Varying Peel Conditions – Low DoIC Summary



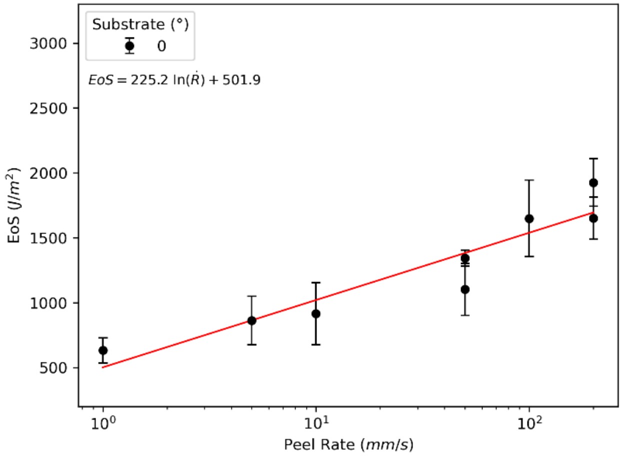
Angled Substrate: Varying Peel Conditions – High DoIC

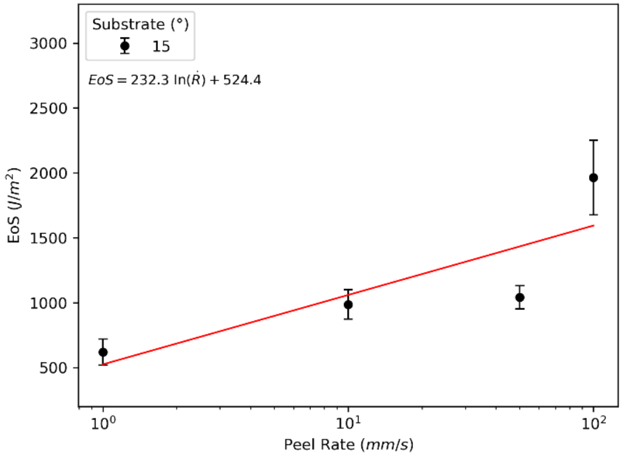
High DoIC Condition:

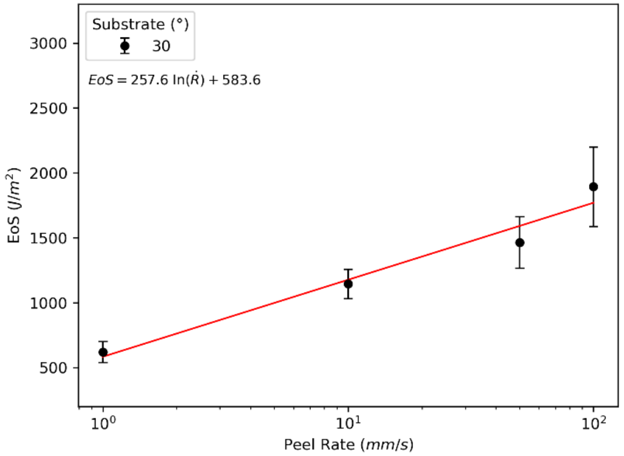
- Temperature: 40 °C
- Deposition Rate: 1 mm/s

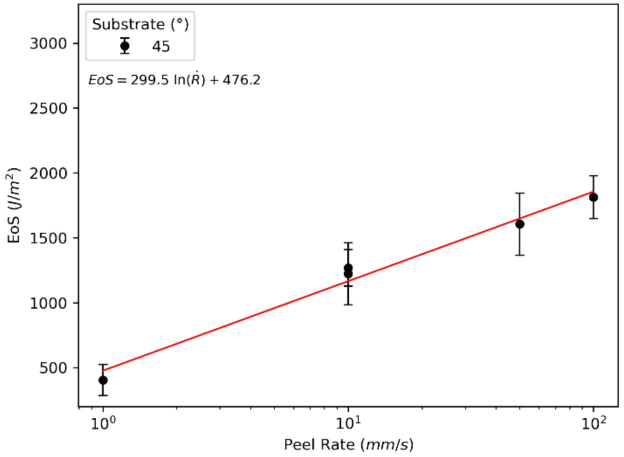
Results for varying substrate angles are shown with respect to 0° tow.

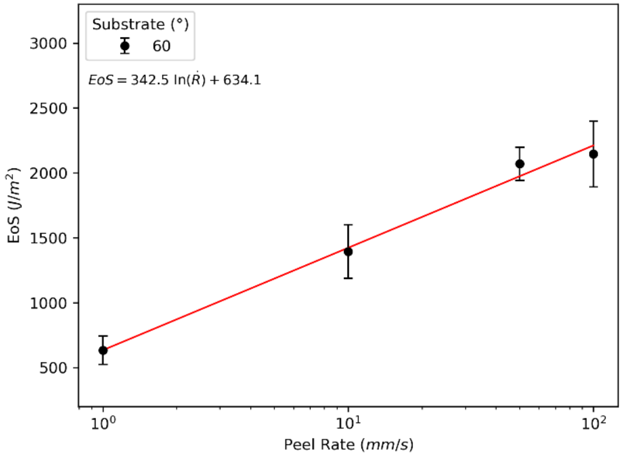
➢ EoS ***increases linearly*** with ***natural logarithm of peel rate*** under conditions with a high Degree of Intimate Contact.

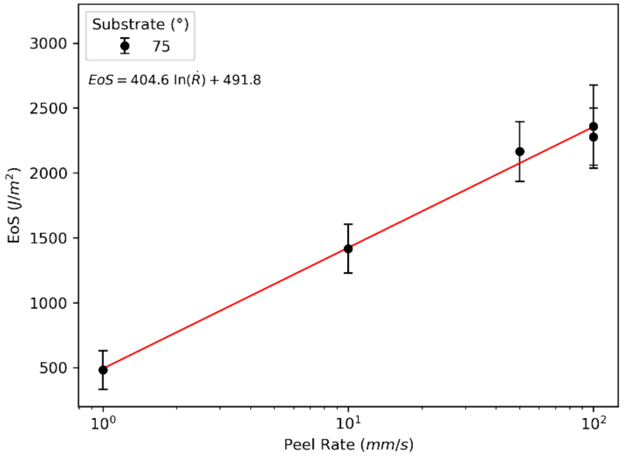


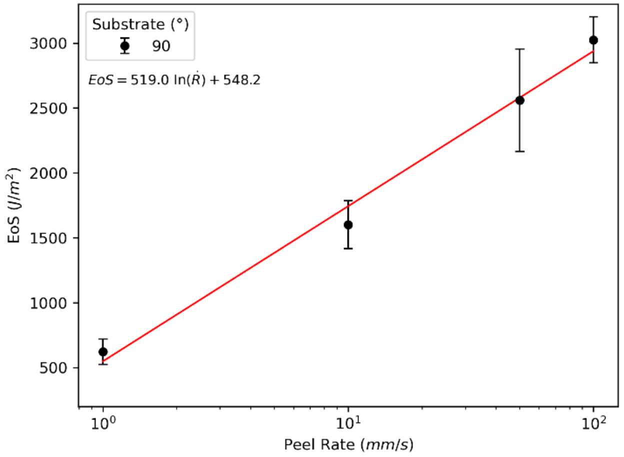




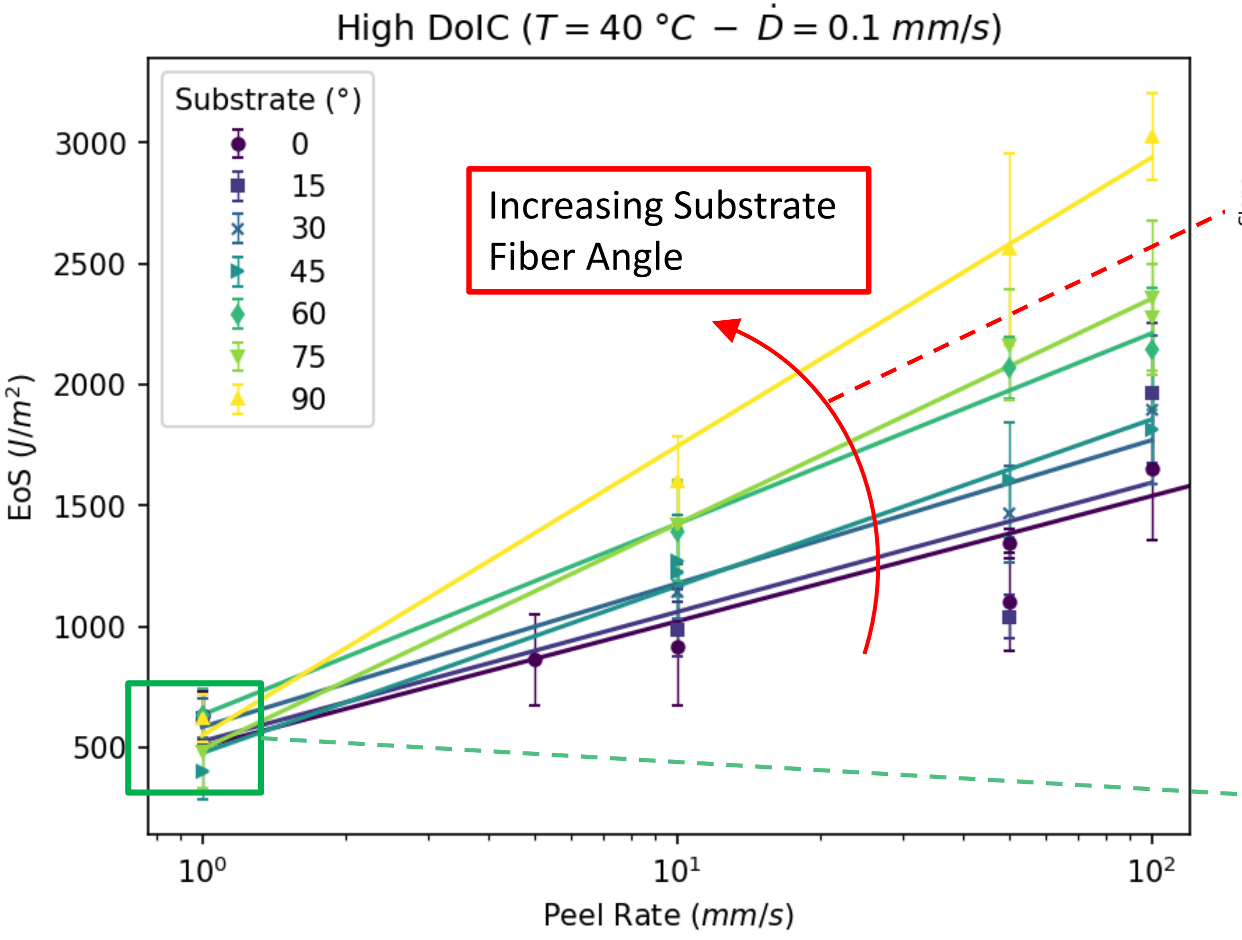


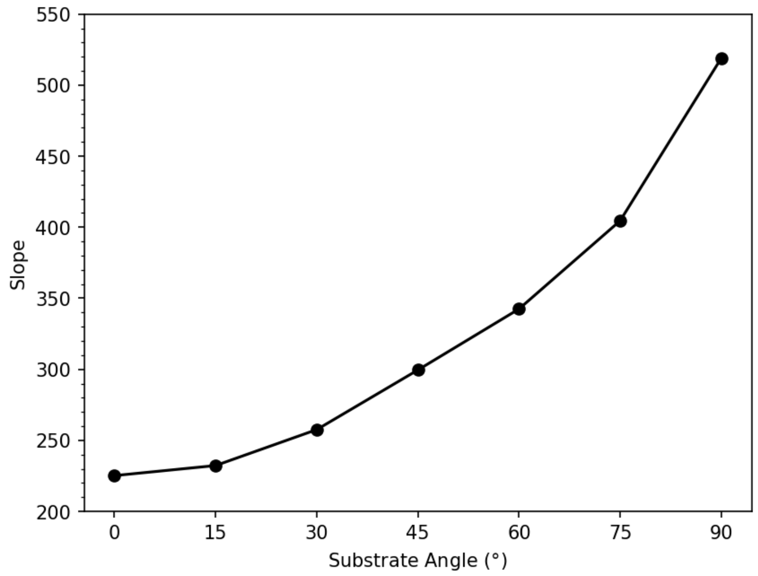






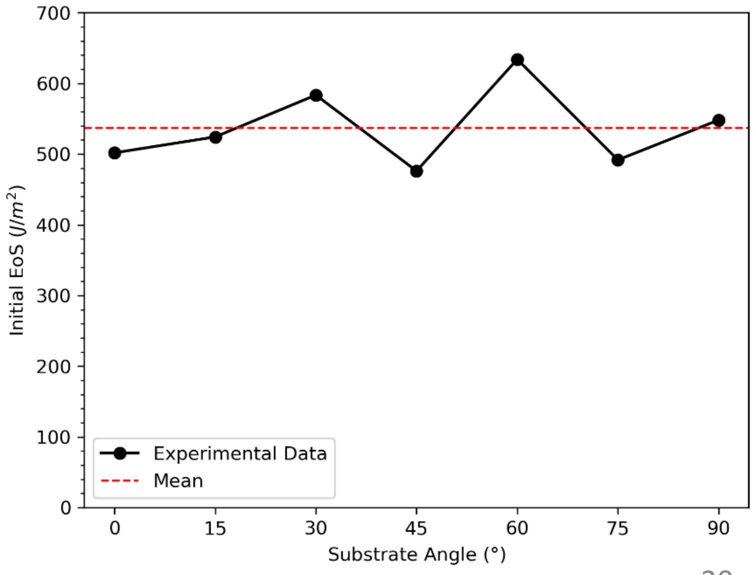
Angled Substrate: Varying Peel Conditions – High DoIC Summary





EoS dependence on substrate fiber angle intensifies with increasing peel rate

Similar behavior at low peel rates



Summary and Outlook

Summary

- The µAFP has been developed as a testbed for scientific study of composites automation. An example of performing in-situ peel tests during the process is presented in this work.
- The in-situ peel test method enabled by the µAFP allows for characterizing tack at high rates up to 700 mm/s, rates that are more representative of AFP processing.
- In-situ peel test method allows for independent characterization of the effects of deposition and peel rates on tack.
- A tack master curve is characterized for the AS4/8552 prepreg system and the independent effects of deposition and peel rate on tack development and resistance are demonstrated.
- Broadly speaking, the results support the assumptions in the Convergent-NASA physics-based tack model framework:
  - Increasing deposition rate, consistently decreases the tack EoS, due to decreasing Degree of Intimate Contact (DoIC).
  - Increasing peel rate increases tack resistance due to resin viscoelastic behavior for high DoIC and for low DoIC appears to reach a shelf value due to limiting viscoelastic behavior.

Future Work

- Future work includes characterization of the effect of substrate orientation, residence time, out-time, internal stresses (e.g., due to steering) on tack.
- Tests with independent deposition and peel rates will be expanded to include a wider range of process conditions.
- The µAFP capabilities can be used to extend and improve physics-based tack models.

Acknowledgements

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