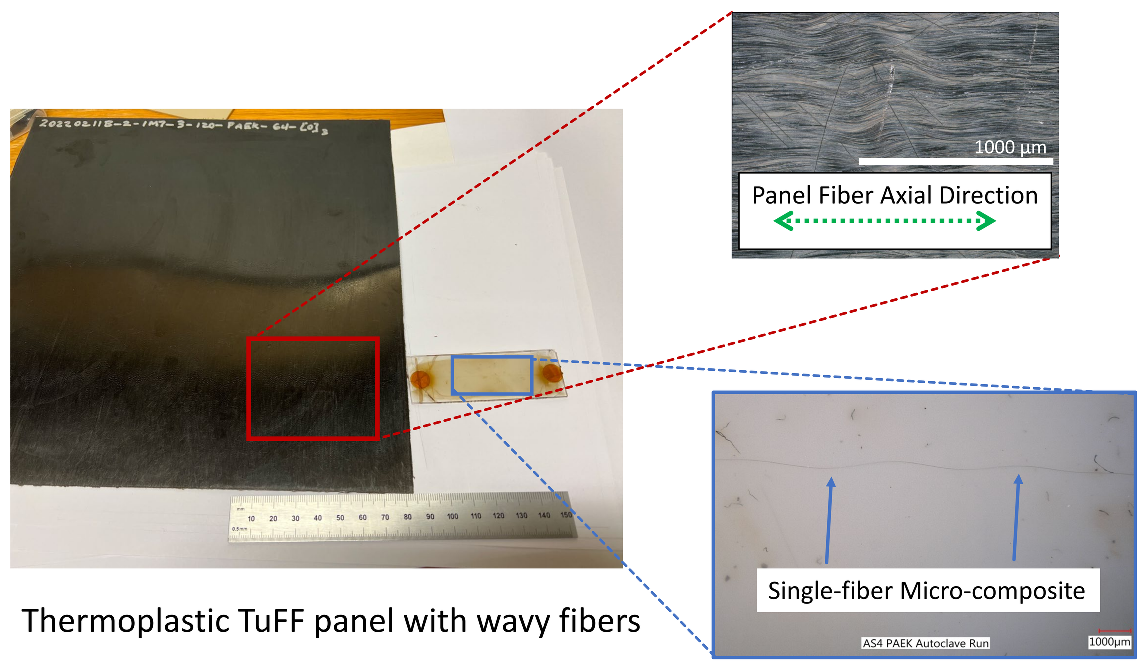
# MICRO-MECHANICAL FIBER WAVINESS DEVELOPMENT IN THERMOPLASTIC CARBON FIBER REINFORCED COMPOSITE PROCESSING

UNIVERSITY OF DELAWARE | CENTER FOR COMPOSITE MATERIALS

**Branndon Chen, (Ph.D.M.S.E.)** [1,2]**, Dr. Nithin K. Parambil**[1]**, Dr. Joseph M. Deitzel**[1]**, and Prof. John W. Gillespie Jr.** [1,2]
University of Delaware | Center for Composite Materials[1] | Department of Materials Science and Engineering[2]

## Introduction

- Poly-ether-imide (PEI) matrix T*u*FF does not exhibit waviness – fibers are straight




Thermoplastic TuFF panel with wavy fibers

- Semi-crystalline low-melt poly-aryl-ether-ketone (LM-PAEK) matrix T*u*FF panels exhibit in-plane waviness after consolidation in autoclave processing conditions shown in the figure below
  - Also shown is a wavy single fiber micro-composite that was processed alongside the composite panel

### Fiber waviness leads to:

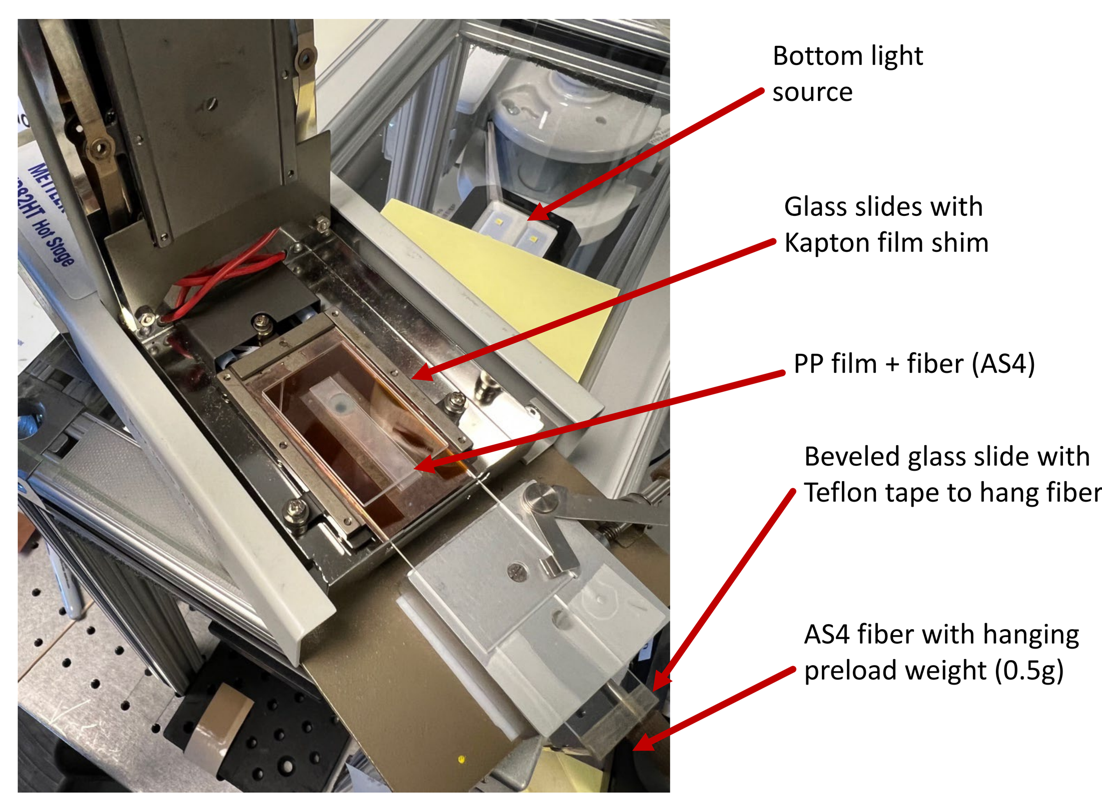
- Increased shear loading of the fiber and matrix interface (IFSS)
- Reduction in modulus and strength
- Larger variability in material static and fatigue performance

### Objectives:

- Visualize and isolate fiber waviness formation using single fiber micro-composites
  - Determine temperature ranges
- Quantify the fiber waviness severity

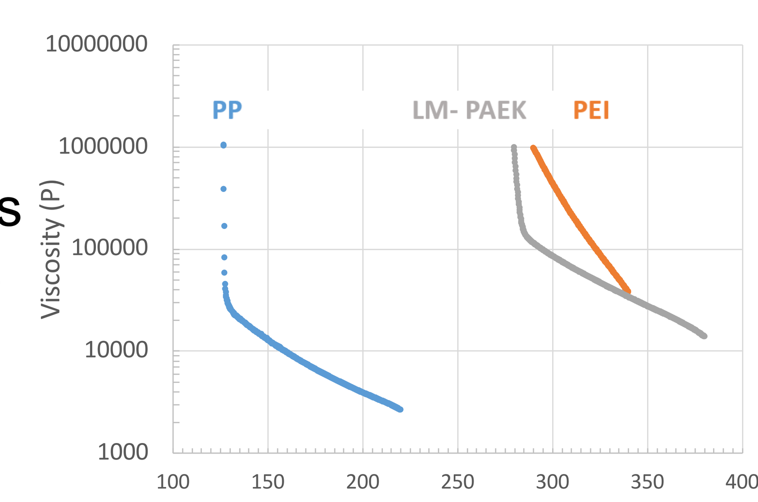
## Experimental

- Utilizing a Mettler hot-stage microscope
  - Controlled cooling rate (20°C/min)
- Iso-tactic polypropylene (PP) $T_{process}$= 220 °C used as model matrix material
  - In addition to LM-PAEK and PEI resins
- Single AS4 carbon fibers were separated
- Pre-tension weight (0.5 g) applied during the beginning of the experiments to keep the fibers straight
  - The preload was removed at various temperatures below the process temperature




Mettler Hot-stage Microscope

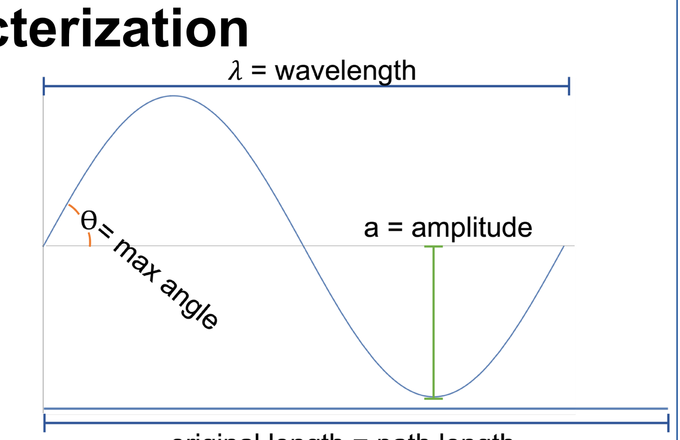
- Polymer melt viscosity was measured via TA Rheometer
- Viscosity measurements were taken as the polymer cooled from process-melt temperature




### Fiber waviness characterization

$y = a\sin(b*x)$   $\lambda$ = wavelength, a = amplitude, b = $\lambda/2\pi$

$\frac{dy}{dx} = a*b\cos(b*x)$




$$\text{Path length} = \int_0^{\lambda}\sqrt{1+\left(\frac{dy}{dx}\right)^2}\,dx$$

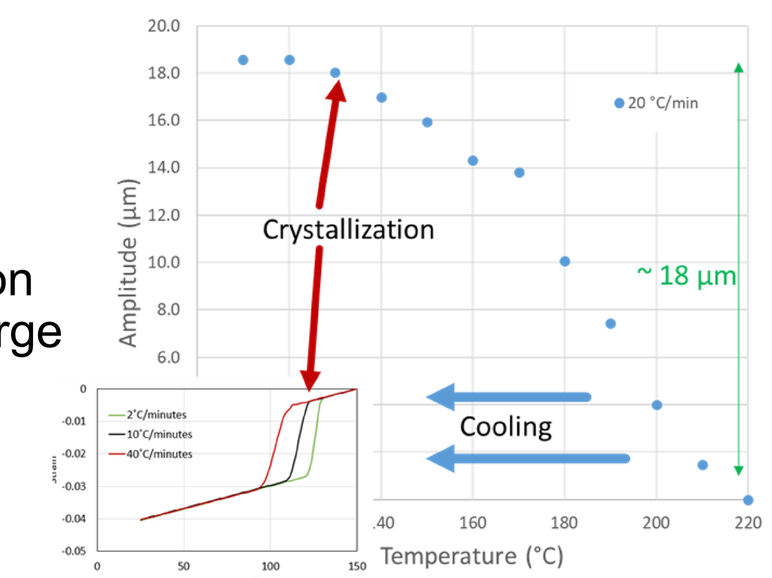
$$\text{Path length} = \int_0^{\lambda}\sqrt{1+(a*b\cos(b*x))^2}\,dx$$

$$\text{Shrinkage strain} = \frac{(\lambda - \text{Path length})}{\text{Path length}}$$

$$\text{Max angle} = \tan^{-1}(a*b\cos(b*x))$$

## Results

- Observing fiber movement (~18μm) from when the preload is removed at 220 °C through crystallization temperature indicates all **fiber waviness formation occurs during the amorphous melt**
  - Fiber movement stops even though the crystallization imparts a large shrinkage strain




- Fiber waviness severity decreases as preload removal temperature is decreased, seen in the micrographs and chart below

**Cooling at 20°C/min**

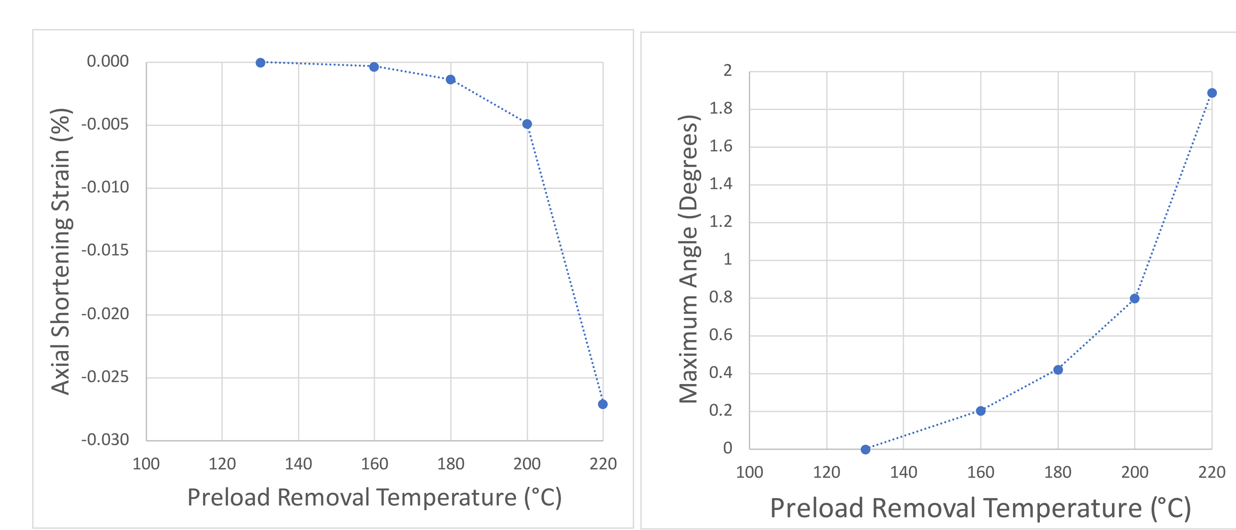
**Preload Removal Temperature:**


220°C Most severe buckling

200°C

180°C

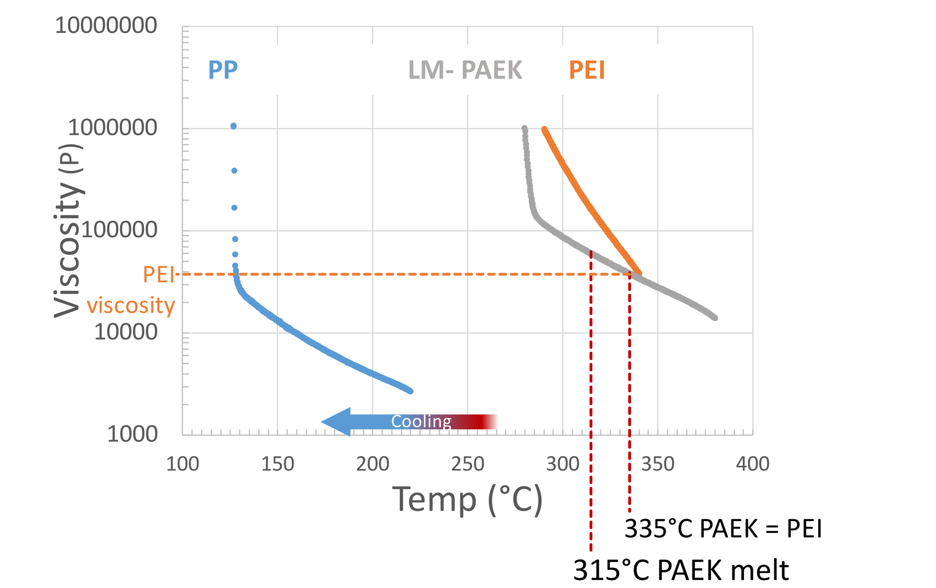
130°C Straight fiber



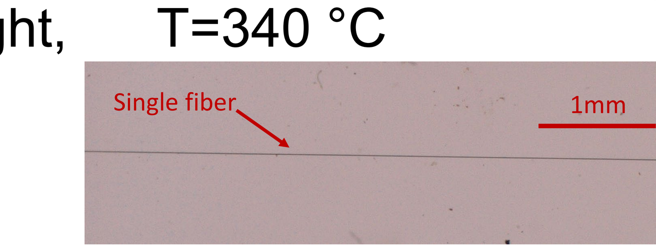

- Shrinkage strain and maximum angle tie together the combinations of wavelength and amplitude the wavy fiber can exhibit
- Amorphous shrinkage and viscosity play a key role in waviness formation
  - Polymer viscosity is low at high $T_{process}$ leading to less resistance to fiber movement
- Critical viscosity of 40,000 P is hypothesized to stabilize the fiber and prevent waviness

## Implications on high-performance aerospace matrix materials

- Minimizing process temperature to minimize melt ΔT and maximize viscosity is important to minimizing fiber waviness




Consistency check: **PEI/AS4** micro-composites remain straight, T=340 °C

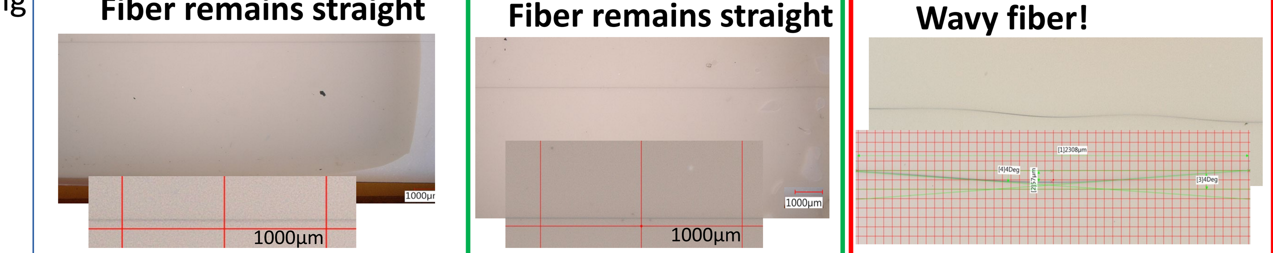



**LM-PAEK:**

Removing at 315°C
ΔT = 315-288 = 27 °C
~ Melt point
**Fiber remains straight**

Removing at 335°C
ΔT = 335-288 = 47 °C
Viscosity PEI=LM PAEK
**Fiber remains straight**

Removing at 380°C
ΔT = 380-288 = 92 °C
$T_{process}$ max
**Wavy fiber!**




## Summary and conclusions

- Novel in situ observation of single fiber waviness formation during the melt has been conducted
- Viscosity and amorphous resin shrinkage are two mechanisms that factor into fiber waviness development
- Observations using a model matrix (PP) have been applied towards LM-PAEK and PEI polymers to control fiber waviness induced by process temperature

## Acknowledgements

*This research was sponsored by the National Aeronautics and Space Administration under Grant and Cooperative Agreement No. 80NSSC20M0164, issued through the Aeronautics Research Mission Directorate, Transformative Aeronautics Concepts Program, University Leadership Initiative.*

*Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration*