SINGLE FIBER WAVINESS DEVELOPMENT DURING THERMOPLASTIC COMPOSITE PROCESSING

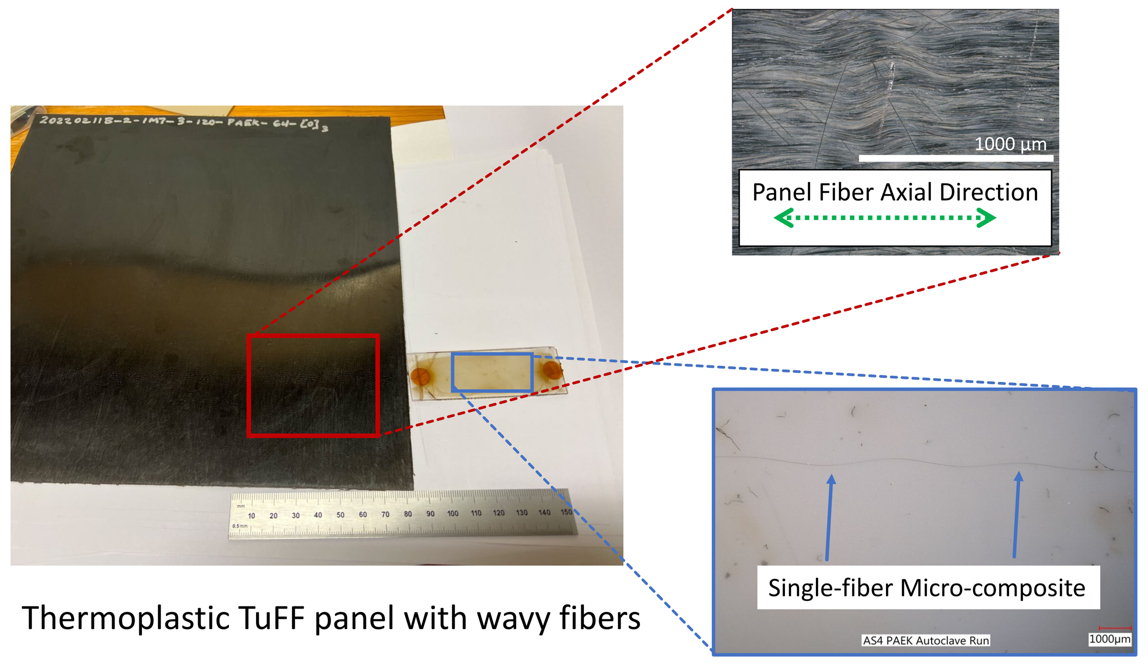
University of Delaware | Center for Composite Materials

Branndon Chen (Ph.D.M.S.E.)[2], Nithin Parambil (P.D.)[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

- Fiber-reinforced thermoplastic composites can exhibit fiber waviness during processing conditions
- 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:

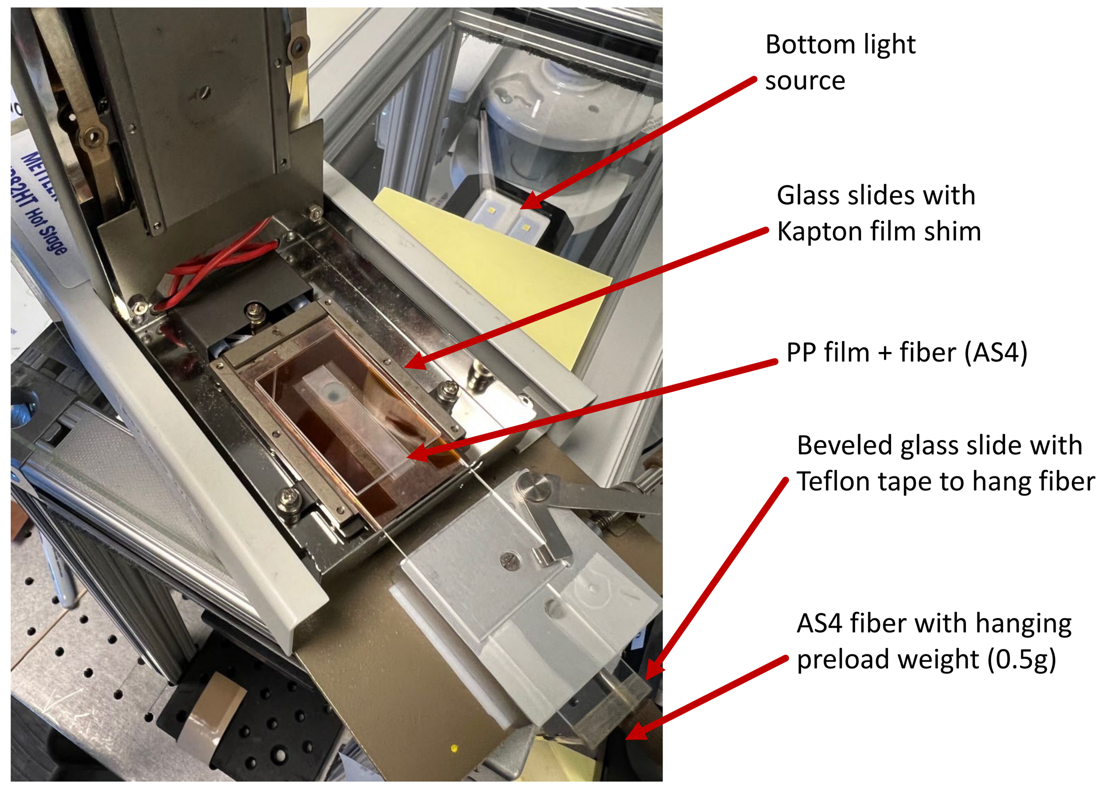
- Increased shear loading of the fiber and matrix interface (IFSS)
- Reduction in modulus and strength
- Larger variability in material static and fatigue performance

Objectives:

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

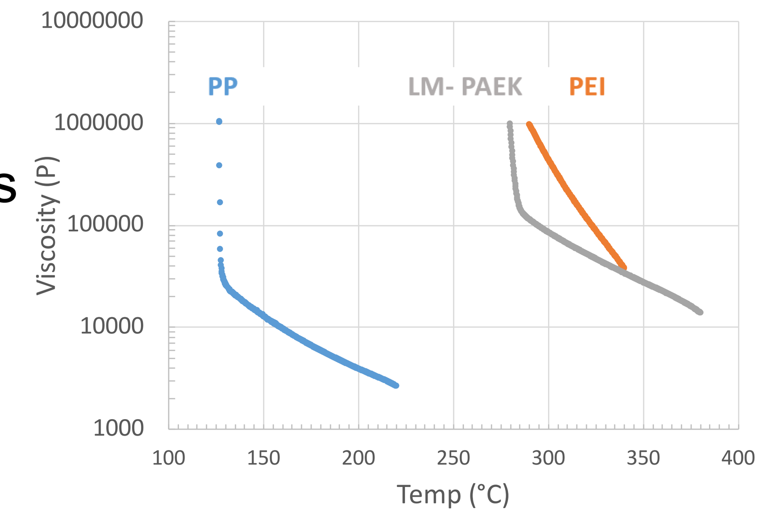
Experimental

- Utilizing a Mettler hot-stage microscope
  - Controlled cooling rate (20°C/min)
- Well characterized model matrix material iso-tactic polypropylene (PP) $T_{process}$= 220 °C
  - In addition to LM-PAEK and PEI resins
- Single AS4 carbon fibers were separated and tabbed so a pre-tension weight (0.5 g) could be applied during the beginning of the experiments to keep the fibers at a straight initial condition
  - 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

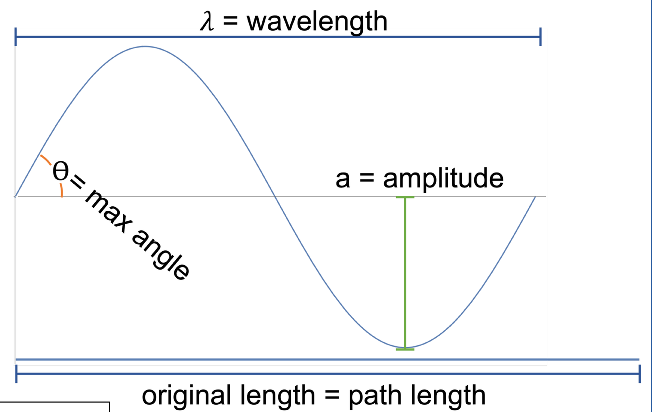


Fiber waviness characterization

$y = a\sin(b * x)$ λ = wavelength

$\frac{dy}{dx} = a * b\cos(b * x)$ a = amplitude, $b = \lambda/2\pi$

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



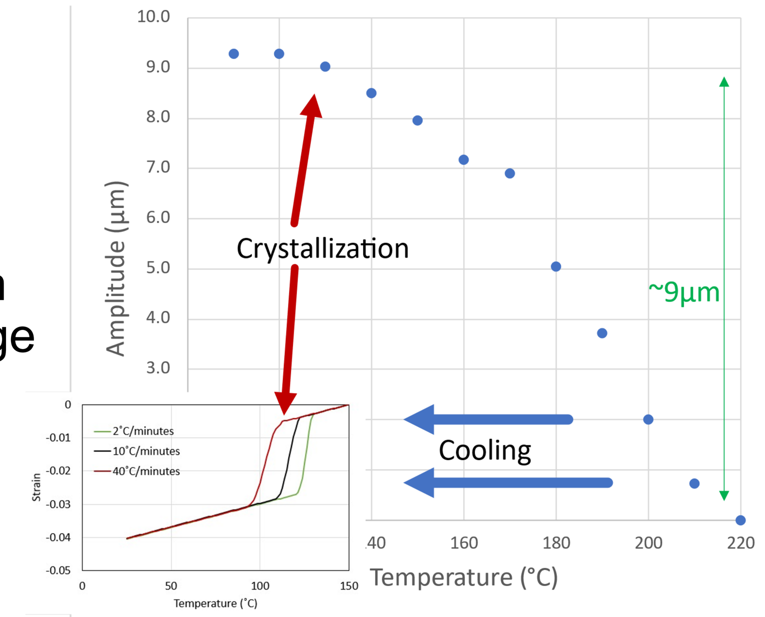
Path length = $\int_0^\lambda \sqrt{1 + (a * b\cos(b * x))^2}\,dx$

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

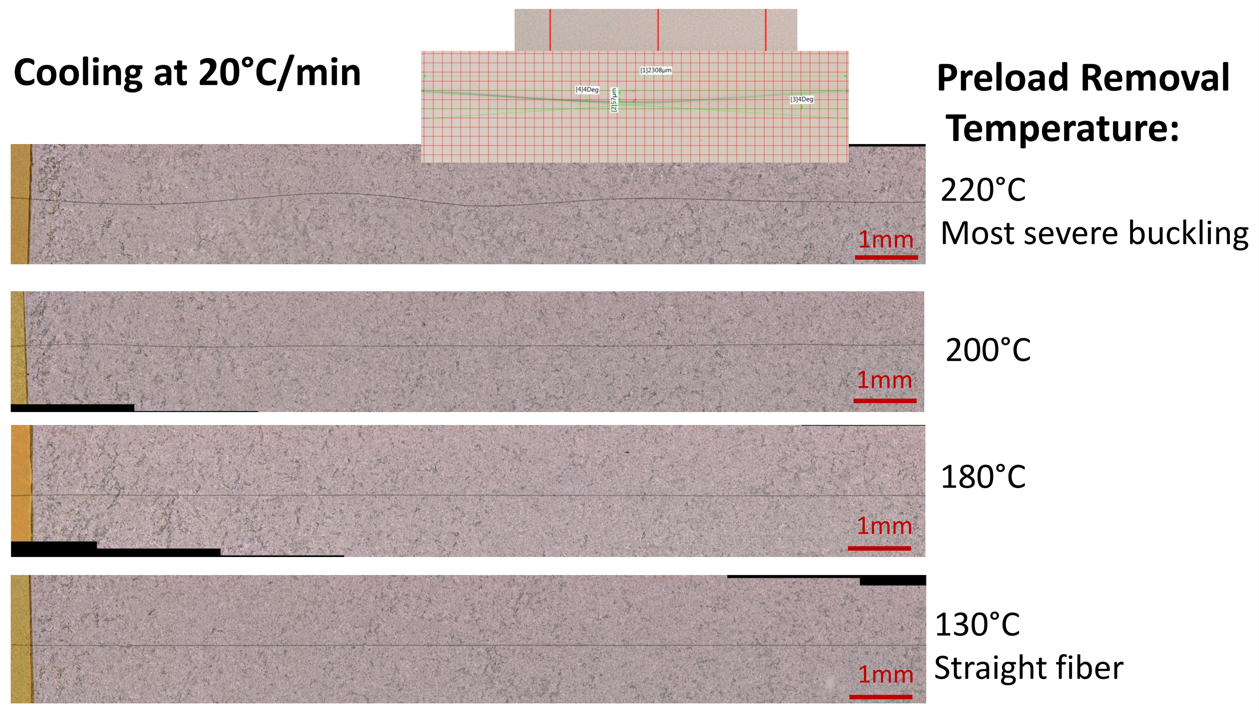
Max angle = $\tan^{-1}(a * b\cos(b * x))$

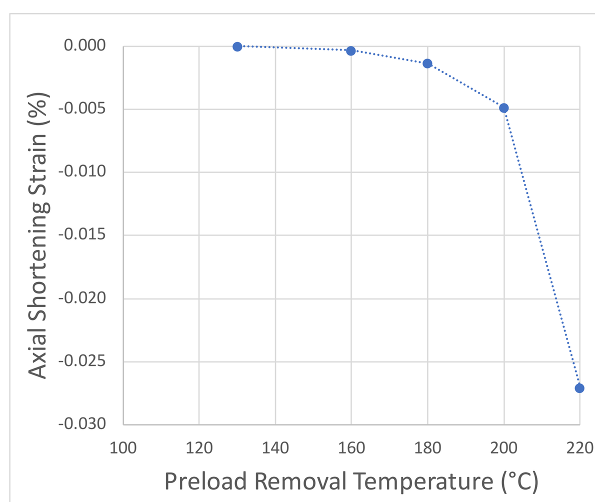
Results

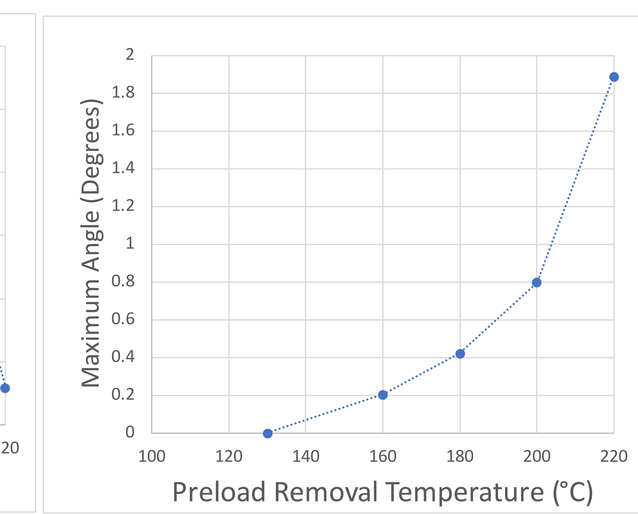
- Observing fiber movement from when the preload is removed at 220 °C through crystallization temperature indicates all fiber waviness formation occurs during the amorphous melt, shown below
  - Fiber movement stops even though the crystallization imparts a large shrinkage strain



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



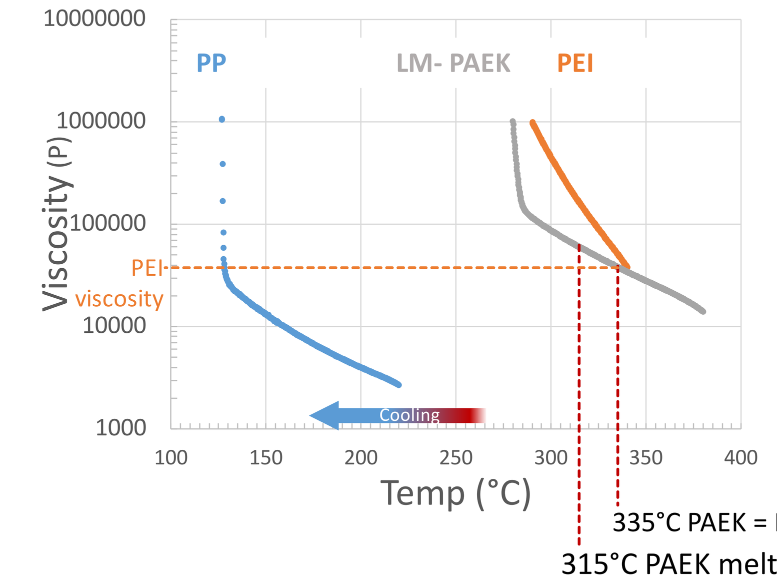




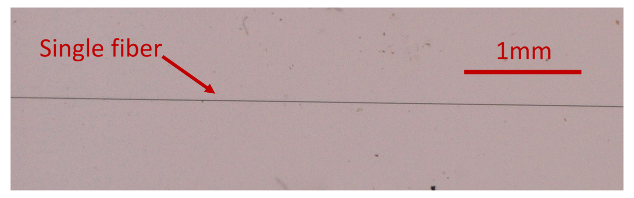
- Shrinkage strain and maximum angle tie together the combinations of wavelength and amplitude the wavy fiber can exhibit
- Amorphous shrinkage and viscosity play a key role in waviness formation
  - Polymer viscosity is low at high $T_{process}$ leading to less resistance to fiber movement

Implications on High-Performance Aerospace Matrix Materials

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

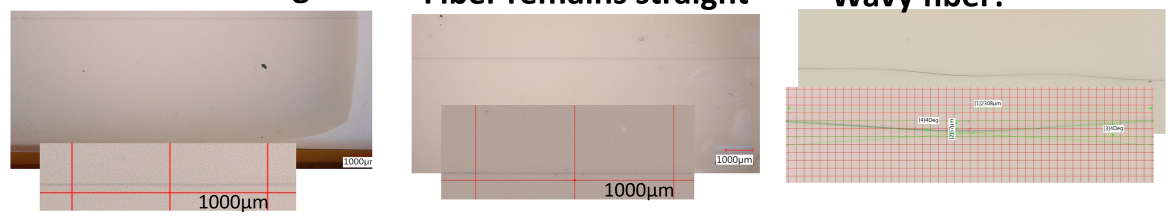


Consistency check: **PEI/AS4** micro-composites remain straight, T=340 °C



LM-PAEK:

Removing at 315°C	Removing at 335°C	Removing at 380°C
ΔT = 315-288 = 27 °C	ΔT = 335-288 = 47 °C	ΔT = 380-288 = 92 °C
~ Melt point	Viscosity PEI=LM PAEK	$T_{process}$ max
Fiber remains straight	**Fiber remains straight**	**Wavy fiber!**



Conclusions

- Novel in situ observation of single fiber waviness formation 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 material is based upon work supported 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.