EXTENSIONAL VISCOSITY OF HIGHLY ALIGNED DISCONTINUOUS FIBER COMPOSITES IN STRETCH FORMING PROCESSES

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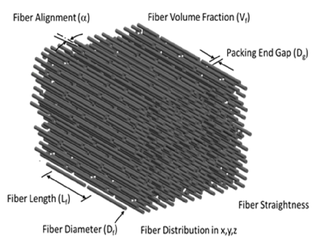
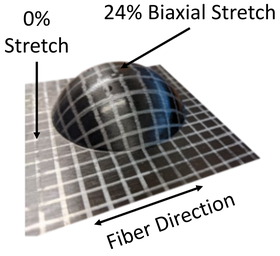
Introduction

Tailored Universal Feedstock for Forming (TuFF) is a novel composite material form consisting of highly aligned short fiber reinforcement. The high degree of alignment results in fiber volume fractions up to 60% and mechanical performance equivalent to aerospace grade continuous fiber composites. Additionally, the discontinuous fiber format allows for stretch forming processes.





This work investigates previously unexplored behaviors under fiber direction stretching. Shearing between neighboring fibers within the melt phase of the thermoplastic matrix is shown to deform viscously. Extensional viscosity was measured as a function of strain rate and temperature. The matrix was then characterized and used in combination with microstructural properties of the TuFF material in order to predict extensional viscosity.

Objectives

- Predict fiber direction extensibility with a generalized micromechanics model
- Apply novel DIC methods to the stretch forming of CF-PEI-TuFF to obtain material constitutive laws $\boldsymbol{L/d = 600}$
  - ULTEM1000 PEI
  - IM7 carbon fibers $\boldsymbol{V_f = 57\%}$
- Validate micromechanics model using experimental data and parameters

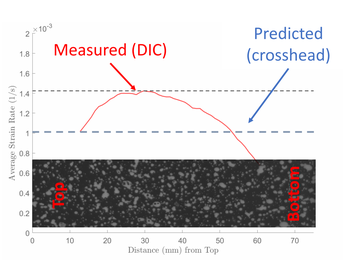
$$\boldsymbol{\sigma_{11} = \frac{F}{A_o}(1+\varepsilon_{11})} \qquad \boldsymbol{\eta_{11} = \frac{\sigma_{11}}{\dot{\varepsilon}_{11}}}$$

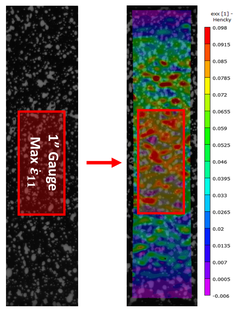
$$\boldsymbol{\eta_{11}\left(\eta_p, \frac{L}{d}, V_f\right)}$$

Methodology

Digital Image Correlation (DIC)

- Crosshead strain measurement underpredicts observed behavior
- DIC reduces gauge section and informs local microstructural variability
- Improved ε_{11} and $\dot{\varepsilon}_{11}$ measurements from DIC are applied to σ_{11} and η_{11} calculations

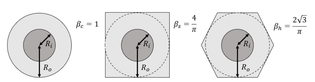




Extensional Viscosity

- Constant $\dot{\varepsilon}_{11}$ and T imparted in environmental chamber
- Stretch to $\varepsilon_{11,max} = 10\%$
- Calculate $\eta_{11,avg}$ from η_{11} values between 1-2% strain

Theory



Carreau Model

$$\eta = \eta_0(1+(\lambda\dot{\gamma})^2)^{\frac{n-1}{2}}$$

Spriggs Model

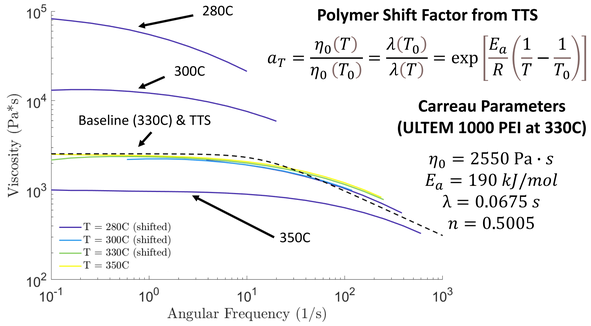
Newtonian: $\eta = \eta_0$ *when* $\dot{\gamma}_{max} \leq 1/\lambda$

Shear thinning: $\eta = K\dot{\gamma}^{n-1}$ *when* $\dot{\gamma}_{min} > 1/\lambda$

$$\frac{\dot{\gamma}_{max}}{\dot{\gamma}_{min}} = (\beta V_f)^{\frac{-1}{2n}}$$

Results

Polymer Rheology



Polymer Shift Factor from TTS

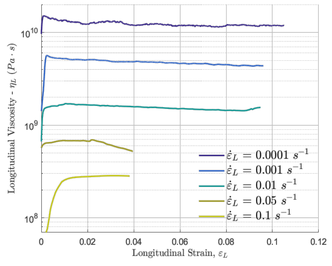
$$a_T = \frac{\eta_0(T)}{\eta_0(T_0)} = \frac{\lambda(T_0)}{\lambda(T)} = \exp\left[\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]$$

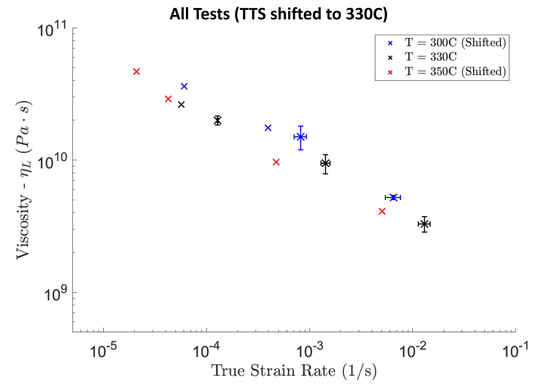
Carreau Parameters (ULTEM 1000 PEI at 330C)

$\eta_0 = 2550\ \text{Pa}\cdot s$
$E_a = 190\ kJ/mol$
$\lambda = 0.0675\ s$
$n = 0.5005$

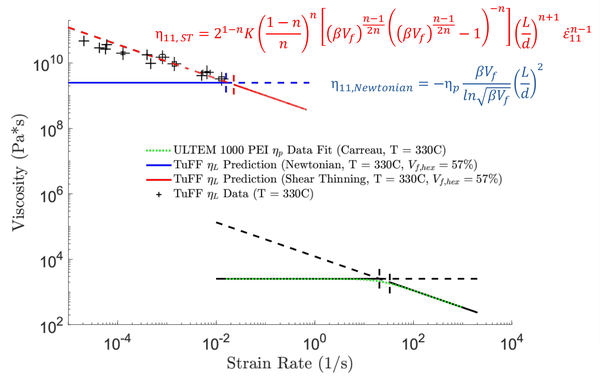
Extensional Viscosity

- Limited strain dependence
- High strain rate and temperature dependence
- Shear thinning behavior





Predictive Model



Conclusions

Polymer Rheology

- Characterized using both Carreau and Spriggs models at 330C
- Obtained shift factors, a_T, from TTS

Extensional Viscosity

- Used DIC methods to accurately measure strain within the gauge section
- Varied by strain rate and temperature only
- Repeatability shown under identical conditions
- Composite “master curve” developed using polymer shift factors exhibited shear thinning fluid behavior

Predictive Model

- Piecewise Spriggs model developed to predict TuFF extensional viscosity from polymer viscosity, fiber volume fraction, and fiber aspect ratio
- Shear thinning prediction fits experimental data
- Model predicts Newtonian behavior at experimental shear rates which contrasts with the TuFF data collected

Path Forward

- Relax model assumptions to align predictions with experimental observations

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.