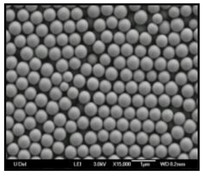
EVALUATING THE HIGH RATE RESPONSE OF A SHEAR THICKENING FLUID USING THE SPLIT-HOPKINSON PRESSURE BAR TECHNIQUE

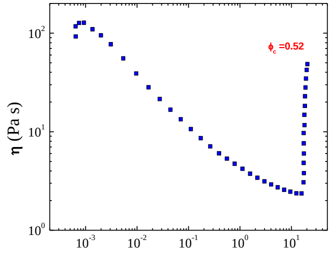
A. S. Lim (PhDMSEG), S. L. Lopatnikov and J. W. Gillespie Jr.

University of Delaware . Center for Composite Materials . Department of Materials Science and Engineering

SHEAR THICKENING FLUID

- **A discontinuous STF thickens rapidly above a critical shear rate.**
  - Spherical silica particles (450 nm)
  - Polyethylene glycol (PEG, 200 MW)
  - 52 vol% silica

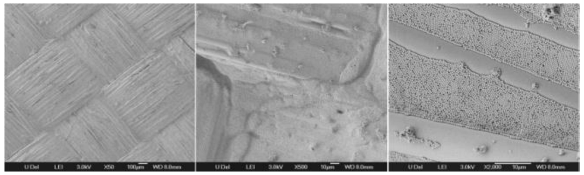




- **Low shear rate rheology:**
  - STF shear-thins prior to transition at ~20 s^{-1}
  - Graph provided by the Wagner Group.

MOTIVATION

- **Goal: To understand and predict the behavior of STF-fabric composites**
  - Evaluate the mechanical response of the bulk STF at high shear rates and stresses characteristic of an impact event.

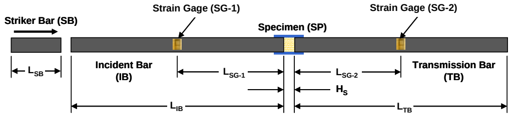


STF-infused fabric at increasing magnifications

- **Standard rheometers can achieve shear rates up to 10^3 s^{-1} in a viscous fluid specimen.**
  - Standard rheometers also unable to capture the transient behavior of a fluid.

SPLIT-HOPKINSON PRESSURE BAR

- **The SHPB consists of a gas gun and three cylindrical bars**
  - Striker bar (SB), incident bar (IB), and transmission bar (TB)



- **The fluid is covered with a rubber balloon to prevent loss during testing.**
  - The balloon allows the fluid to expand radially, thus the applied compression induces shear within the fluid.
- **Through the SHPB technique, it is possible to evaluate the mechanical response of a fluid specimen at shear rates over 10^5 s^{-1}.**

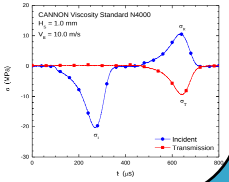
CLASSIC SHPB DATA REDUCTION

- The equations below are used to determine the average force and displacement rate during testing

$$F = \frac{1}{2}\left[A_{IB}E_{IB}\left(\varepsilon_I + \varepsilon_R\right) + A_{TB}E_{TB}\varepsilon_T\right]$$

$$\dot{U} = \dot{U}_1 - \dot{U}_2 = C_{0,IB}\left(-\varepsilon_I + \varepsilon_R\right) + C_{0,TB}\varepsilon_T$$

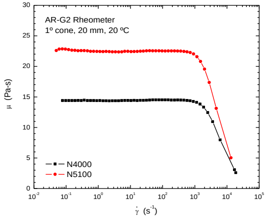
- Conditions under which these equation may be applied:
  - Strong transmitted signal
  - Strain rate must not exceed inverse travel time
  - Fluid must be in equilibrium

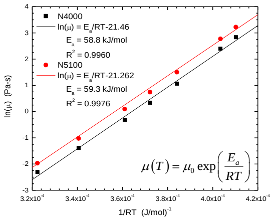


- The first two are easily met.

NEWTONIAN FLUID

- The CANNON N4000 Newtonian viscosity standard was used to validate the SHPB technique
  - 100% polybutene
  - Chosen for its viscosity at room temperature which corresponds well with the STF

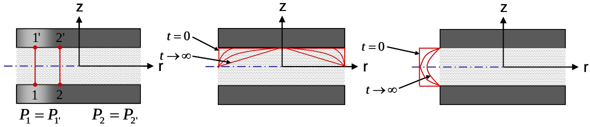




- Temperature rise was found to be <1ºC during testing.

DYNAMIC PROCESSES

- Two equilibrium processes must be considered:
  - Pressure relaxation (through the specimen thickness and across the radius)
  - Poiseuille flow profile development



$$\tau_H = \frac{H_S}{c} \qquad \tau_P \approx \frac{\nu R^2}{c^2 H_S^2} \qquad \tau_V \approx \frac{H_S^2}{\nu}$$

$$\tau_R = \frac{R}{c}$$

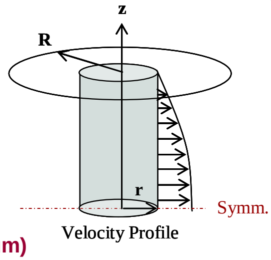
- This time is 13.6 μs for N5100 tested with H_S = 0.5 mm and R = 9.5 mm.

The experimental timescale is ~200 μs.

HIGH RATE CHARACTERIZATION OF A SHEAR THICKENING FLUID (STF) USING HOPKINSON BAR METHODOLOG

Continued

SQUEEZE FLOW MODEL



- ♦ A quasi-stationary model assuming fully developed flow was used to predict experimental results.
  - ✧ Conservation of mass

$$\frac{1}{r}\frac{\partial(rV_r)}{\partial r}+\frac{1}{r}\frac{\partial V_\theta}{\partial_\theta}+\frac{\partial V_z}{\partial z}=0$$

  - ✧ Navier-Stokes (momentum)

$$\rho\left[\frac{\partial V_r}{\partial t}+V_r\frac{\partial V_r}{\partial r}+V_z\frac{\partial V_r}{\partial z}\right]=-\frac{\partial P}{\partial r}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(rV_r)}{\partial r}\right)+\frac{\partial^2 V_r}{\partial z^2}\right]$$

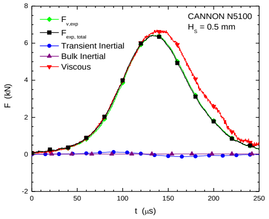
- ♦ Solving this system of equations yields:

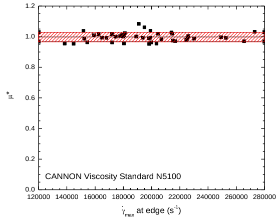
$$F=\underbrace{\frac{\pi\rho R^4}{8h}\left(\ddot{U}_1-\ddot{U}_2\right)}_{\text{transient inertial}}+\underbrace{\frac{9\pi\rho R^4}{40h^2}\left(\dot{U}_1-\dot{U}_2\right)^2}_{\text{bulk inertial}}+\underbrace{\frac{3\pi\mu R^4}{2h^3}\left(\dot{U}_1-\dot{U}_2\right)}_{\text{viscous}}$$

- ♦ It is assumed that there is no slip between the bars and fluid upon which zero body forces act.

SHPB VALIDATION

- ♦ The viscous and inertial forces predicted by the squeeze flow model are plotted along with the experimental force.

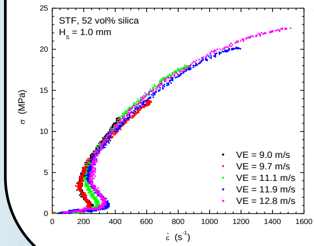


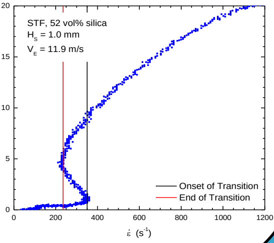


- ♦ Matching the viscous and experimental force curves yields a *theoretical viscosity*.
  - ✧ This value was then normalized by the actual fluid viscosity during testing.
  - ✧ The results for 50 tests are plotted (right)
  - ✧ A normalized viscosity of 1 represents an ideal match between theory and experiment.

STF BEHAVIOR - TRANSITION

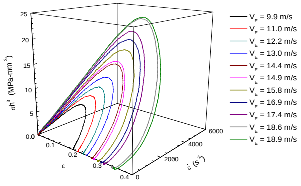
- ♦ Five STF specimens were examined at different loading rates and from this data, the transition boundaries for the STF were identified.
  - ✧ The onset of transition occurs at the first strain rate maximum.
  - ✧ Beyond this point, the material stiffens (impedance increases and bar end velocities initially decrease) while the load is monotonically increasing.





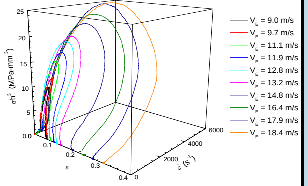
STF MECHANICS

- ♦ Newtonian vs. STF behavior is illustrated using 3D stress-strain-strain rate plots, which allow for the visualization of constitutive relationships.



Pure viscous

$$\sigma=f(\dot{\varepsilon})$$

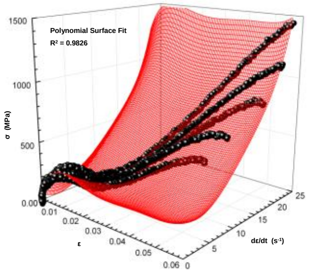


Nonlinear viscoelastic

$$\sigma=f(\varepsilon,\dot{\varepsilon})$$

STF MODELING

- ♦ STF loading behavior surface fitted with a 5th order polynomial expression.
- ♦ Approaches:
  - ✧Fit surface with known expressions.
  - ✧Develop spring and dashpot model representing STF behavior.
  - ✧Separate initial (viscous) behavior from the final (viscoelastic) behavior and model the two separately.



FUTURE WORK

- ♦ Develop a constitutive relationship. describing the behavior of STF at high rates.
- ♦ Examine different concentrations to determine the effect of particle loading on transitional behavior.
  - ✧ Gain insight into the nature of fluid-solid (viscous-viscoelastic) transition.

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