Metalworking Fluids Research at UIUC

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University of Illinois at Urbana-Champaign
Research Sponsors

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Metalworking Fluids (MWF) Research at UIUC

Macro/Micro-Scale Machining

Microfiltration
- Synthetic MWF
- Semi-synthetic MWF

Synthetic MWF
- Understanding the Mechanism of Productivity Loss During Recycling
- Effects of Selective Depletion of Contaminants

Performance Evaluation
- MWF Functionality Evaluation
- Transiently Stable Emulsions

Atomization-based Cutting Fluid System
- mMT Machine Tool Design
- Cutting Fluid Application System

Cooling and Lubrication Through Atomization
- Spreading Behavior of MWF Droplets on a Rotating Surface
- Performance Evaluation

Semi-Synthetic MWF
- An Investigation into the Partial Blocking Mechanism to Understand Flux Decline
- Three-Dimensional Fluid Dynamic Models to Investigate Pore Blocking and Flux Decline
Presentation Outline

- Metalworking Fluids (MWFs) Use
- MWFs Use Issues
- Microfiltration of MWFs
  - Synthetic MWF
  - Semi-synthetic MWF
- Atomization-based Cutting fluid Application in Micro-machining
Metalworking Fluid Use

400 ML of cutting oil per year in U.S. – why are they being used?

– Cooling
– Lubrication
– Corrosion Inhibition
– Chip Flushing
Metalworking Fluid Benefits

- Increased Tool Life
- Improved Surface Finish
- Increased Dimensional Accuracy
- Reduced Cutting Forces
- Improved Machine Tool Life and Function
Metalworking Fluid Types

Three common types of water soluble MWFs

- **Soluble oils** – 46% of all manufactured
  - 60-90% Mineral Oil with balance made up of emulsifiers

- **Semi-Synthetics** – 19% of all manufactured
  - 2-30% mineral oil with balance made up of emulsifiers and water

- **Synthetics** – 12% of all manufactured
  - No mineral oil
  - 5-10% emulsifiers with balance made up of water

Synthetics and Semi-Synthetics are increasing in market share at the expense of Soluble oils.
Concern #1 – Health Effects

- 1.2 million exposed to cutting fluids [Hands]
- Airborne particulate standard: now 5 mg/m³ – could change to 0.5 or 0.1 mg/m³ [United Auto Workers]
- Bacteria / fungi in fluid produce toxins [Thorne]
- Biocides can cause dermatitis
- High profile lawsuits
Concern #2 – Environmental Effects

- Spent cutting fluid disposal – waste water – contamination
- Biochemical action (BOD, COD, etc.)
- Spills and Leaks (e.g., from chips and splashing)
- Rivers, lakes, and ground water contamination
Approaches to MWF Use

- **Eliminate Use**
  - Dry Drilling

- **Reduce Use**
  - Minimum Quantity Lubrication
  - Micro-lubrication

- **Reduce hazard of standard MWF use**
  - Microfiltration

- **Re-think traditional MWFs**
  - Supercritical CO$_2$, etc.
Microfiltration of MWFs

DeVor/Kapoor Research Group’s work started with Steve Skerlos and a relationship with Kishore Rajagopalan at the Illinois Waste Management and Research Center (WMRC, now Illinois Sustainable Technology Center).

Goal: Reduce human health and environmental impact through fluid life extension and microbial population reduction.
Microfiltration Basics

- **Permeate**: clean fluid that has been passed through membrane
- **Feed**: dirty fluid that flows across membrane
- **Flux**: rate of flow through membrane given in $L/m^2/hr$ (LMH)
- **Transmembrane Pressure**: pressure difference between permeate and retentate sides of membrane
- **Cross-Flow Velocity**: rate of flow across membrane surface
Microfiltration Benefits

- Can reduce microbial concentration by more than 7-log.
- 50-95% endotoxin reduction.
- Significant reduction of tramp oil contamination.

Rajagopalan et al., 2004
Membrane Fouling

- Primary obstacle to efficient use of microfiltration technology is the fouling of the membrane pores by contaminants and/or fluid components [Belfort 1994, Rushton 2000].

- In order for microfiltration to become a viable technology the mechanisms that cause membrane fouling must be understood.
Research Objectives and Scope

1. Objectives
   1. To develop a better understanding of the membrane fouling mechanisms present in the microfiltration of MWFs
   2. To improve the technology by developing a model that will illuminate the membrane and fluid characteristics that lead to membrane fouling.

2. Scope
   1. Synthetic and Semi-synthetic MWFs, and aluminum oxide microfiltration membranes.
   2. Low transmembrane pressures and high cross-flow velocities
Microfiltration Research: Synthetic MWFs

(Dr. Steven Skerlos, 2000)
# MWF and Membrane Material

## Synthetic MWF Formulation

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<tr>
<th>Component</th>
<th>Concentration (%)</th>
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<tr>
<td>Water</td>
<td>50 – 80</td>
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<tr>
<td>Triethanolamine</td>
<td>5 – 20</td>
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<tr>
<td>Amine dicarboxylate</td>
<td>5 – 20</td>
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<tr>
<td>Chelating agent</td>
<td>&lt; 2</td>
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<tr>
<td>pH Buffer</td>
<td>&lt; 5</td>
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<tr>
<td>Wetting agent</td>
<td>&lt; 1</td>
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<tr>
<td>Lubricant additive</td>
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<tr>
<td>Defoamer</td>
<td>&lt;0.5</td>
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<tr>
<td>Biocides (1-3 used)</td>
<td>&lt; 2</td>
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</table>

**Base Fluid**

**Specialty Additives**

Membrane: Alpha-phase Aluminum Oxide with a pore size of 0.2 microns
Full Synthetic MWF Flux vs. Time and Pressure

Initial Water Flux = 540 LMH

Synthetic MWF Flux vs. Pressure

\[ J = \frac{\Delta P}{0.156 + 0.00002(\Delta P)^{2.42}} \]

- 15 psi, A5
- 25 psi, A3
- 40 psi, A4
- 40 psi, A6
- 15 psi, A2
- 40 psi, A1

Department of Mechanical Science and Engineering
Impact of Lubricant Additive and Defoamer on Flux of Initial Base Fluid/Biocide Mixture

- Specialty additives such as lubricant additives and defoamers, and biocides cause flux decline.
- Evidence of residual effects between experiments.
- Final flux depends on lubricant and defoamer, not on base fluid or biocides.
Flux vs. Time at Different MWF Concentrations

- Minor concentration variation has major impact on flux
Other Mechanisms of Flux Decline

Four fouling mechanisms are generally seen in microfiltration [Belfort 1994]

- **Pore Constriction**
  - Foulant becomes deposited on pore walls decreasing cross-sectional area

- **Pore Blocking**
  - Physical blocking of a pore by a particle larger than pore diameter.

- **Cake Formation**
  - Particles greater than pore diameter buildup and create a layer on the surface of the membrane
Adsorption leading to pore constriction is the dominant mode of flux decline for uncontaminated synthetic MWFs.
**pH Dependent Swelling of Residual Anionic (Polyglycol) Lubricant**

- **Residual lubricant pH=5.5**
  - Pores open for permeation
  - Normal flux observed

- **Residual lubricant pH=10.5**
  - Considerable pore constriction evident due to lubricant swelling.
  - Low flux observed.
Summary of Flux Decline Experiments

- Base fluid ingredients only cause flux decline if the membrane has been previously exposed to specialty additives.

- The lubricant additive, defoamer, and biocides used in this formulation cause significant flux decline.

- The observed membrane performance decline is not due to foulant material permanently plugging the pores.

- Adsorption of synthetic MWF specialty additives leads to pore constriction and productivity loss.

- Increasing the hydrophilic to hydrophobic ratio in the copolymers can decrease flux.
Microfiltration Research:
Semi-Synthetic MWFs

(Dr. John Wentz, 2008 and S. Ham, 2009)
Experimental Materials

- **Metalworking fluid**
  - Castrol Clearedge 6519
  - 2-3% oil
  - 1% emulsifiers
  - <1% corrosion inhibitors
  - <1% biocide
  - 96-97% water
  - 28nm average particle size

- **Membrane**
  - Aluminum oxide tubular ceramic membrane
  - Cutoff pore size of 500nm and 800nm
Experimental Setup

- Transmembrane Pressure controlled by ball valve.
- Cross-Flow Velocity controlled by gear pump
Experimental Design: Intensity and Mode of Fouling

- Measure membrane fouling rate and level of final steady state flux
- Look at runs of different concentrations (1%, 3%, 5%)
- Constant operating conditions
  - 0.255 bar transmembrane pressure
  - 6.0 m/s cross-flow velocity
- Run tests for two membrane pore sizes.
  - 500nm
  - 800nm
Flux Results

- Two stages of fouling
  - Exponential flux decline
  - Slowly moves to steady-state
  - Different types of membranes and fluids have different flux decline curves.

![500 nm Membrane Flux Graph](image)

![800 nm Membrane Flux Graph](image)
SEM Images of Membrane

Scanning electron microscope images were taken of membrane surface to provide visual evidence of fouling progression.

New membranes show open pore structure

40,000X Magnification

20,000X Magnification
Partial blocking is illustrated by particle aggregates near pore openings.

**40,000X Magnification**

**Stage One: Aggregate Deposition**

**20,000X Magnification**

Wentz et al. 2005, Trans. NAMRI
SEM Images of Aggregate Layer

Aggregate layer shows very closed membrane surface covered in particles.

Stage Two: Aggregate Layer

40,000X Magnification

20,000X Magnification

Wentz et al. 2005, Trans. NAMRI
Summary of Experimental Work

- Experimental results of microfiltration tests indicated that membrane fouling was caused by:
  - Initial pore constriction/partial blocking due to aggregate deposition within the pores
  - Pore blocking due to the formation of an aggregate layer on the membrane surface

- The particle size distribution was shown to change over the time a test was completed
  - Aggregates large enough to totally block pores were formed
  - Large aggregates were not found in the permeate

NEXT STEP: Develop a Model to Understand the Underlying Mechanism of Fouling
Partial Pore Blocking

- Particles not large enough to fully block the pores still cause fouling.
- Get stuck in the tortuous interconnected pathways of the pores.
Dynamic Simulations of Aggregate Motion

- Pore was modeled after SEM images of the membrane surface.
- Pore model showed representation of tortuosity, porosity, and multiple inlets and outlets.
- CFD software (Fluent 6.2.16) was used to simulate the continuous phase flow through the pore area based on hydrodynamic as well as Brownian and Electrostatic forces.
- Constant velocity was assumed at the pore inlet.
- Negative pressure differential was assumed at the pore outlets.
- Flow field was solved for Stokes flow due to Re $<< 1$
Particle trajectory change due to Brownian motion: (a) Hydrodynamic only; (b) Hydrodynamic and Brownian motion Simulation Results (Surface potential -50V)

Brownian force caused the particle’s trajectory to change and the particle to block a different pore outlet
Particle trajectory change due to electrostatic force (black areas are stuck particles): (a) Hydrodynamic only; (b) Hydrodynamic and Electrostatic forces

- Electrostatic force caused the particle to pass further away from previously deposited particles
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Progressive Fouling Simulation Including Hydrodynamic, Brownian and Electrostatic Forces (Surface Potential -50V)
Progressive Fouling Simulation Including Hydrodynamic, Brownian and Electrostatic Forces (Surface Potential -50V)
3-D Model to Predict Flux Decline

- Disk pore was modeled to better understand how fouling and flux proceed.
- First model for unfouled membrane and second model for partially blocked membrane.
- Pore size distribution were based on 500nm sintered α-alumina membrane.

a) Geometry for initial membrane; b) geometry for partially blocked membrane
Simulation Results

Flux decline for initial pore size distribution

Flux decline for partially blocked pore size distribution

• The flux decline of disk model compares favorably with experimental results
Application to Membrane Design

- Disk model was used to see the effect of pore size distribution on flux decline.
- Disk 1 has the same pore size distribution as used for unfouled membrane and Disk 2 was designed to have the pore size distribution with a few large pores and many small pores.
Simulation Results

- Disk 1 model exhibited a gentler flux decline than Disk 2 model
Conclusions

1. A three-dimensional fluid dynamic model of particle motion that includes the action of hydrodynamic, electrostatic, and Brownian motion forces was developed to predict flux behavior in membranes.

2. It was shown that partial blocking within a three-dimensional single-passageway pore geometry allows flow to continue though partially blocked pores because they do not become completely sealed.

3. The model for a multiple-disk pore geometry was shown to predict flux decline to an eventual non-zero steady state flux value. This compares favorably with published experimental results.
**Drive for Miniaturization**

*Increased need to fabricate miniature components and/or miniature features*

**Length scales:** <500 μm length, <125 μm diameter, <50 μm width

**Materials:** Stainless steel, Aluminum, Brass, Titanium (often with complex 3-D features)

**Manufacturing Processes:** Mechanical machining, EDM, Laser Machining, Lithography, Etc.
Micro-Machining

Micro-machining processes are characterized by mechanical interaction of a tool with workpiece material, causing shearing of tool material along defined tool paths, eventually leading to removal of the workpiece material in the form of chips.

Including:

- Micro-turning
- Micro-drilling
- Micro-milling
UIUC 3-Axis mMT

- Y motor (1 of 2)
- Counterbalance
- X motor (1 of 2)
- Workpiece mount
- Z motor (1 of 2)
- Spindle

- 180x180x300mm machine
- 25x25x25mm of travel
- Less than 0.5 µm/N static compliance at workpiece
Development of Cutting Fluid Application System for Micromachining

Problem

- Increased rubbing and ploughing – increased friction
  - A good lubricating property of the cutting fluid is essential
- It is likely that traditional macro-machining process cutting fluid systems such as flood and high-pressure coolant application are not viable approaches in micro-machining.
  - The impact force of the coolants may be greater than cutting forces that are only on the order of a few Newtons
- Small size chips
  - Conventional methods may create a slurry that can affect with both the cutting process and the resulting part quality

Solution

- Atomization-based cutting fluid application system
Atomization-Based Fluid Application

- An atomization-based method as a cutting fluid application system based on ultrasonic vibration is considered
  - Atomized droplets access the cutting zone, absorb heat while acting as a lubricant, and remove heat from the cutting zone through evaporation
  - Spray cooling has been found to be very effective in cooling of electronic circuits (> 100 W/cm²)

- Droplet characteristics
  - Droplet size, distribution, and velocity

- Droplet characteristics affect
  - Cooling capability
  - Impingement dynamics (film formation)

- Impingement dynamics can influence lubricating capability
Experimental Setup and Design

- Experiments to examine viability of the system
  - Comparison with dry cutting
  - Comparison with flood coolant
  - Cutting temperature comparison

- Force measurement: Kistler 9018 load cell

- Wear and burr observation: Hirox CX-10C optical microscope

- Temperature measurement: Analog Devices Type E thermocouple

**Experimental condition**

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<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Spindle speed</td>
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<tr>
<td>Radial depth of cut</td>
<td>Full immersion cutting</td>
</tr>
<tr>
<td>Tool diameter</td>
<td>508 µm</td>
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<tr>
<td>Cutting fluid</td>
<td>DI / 5% Castrol 6519</td>
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<tr>
<td>Workpiece</td>
<td>Aluminum 7075 / steel 1018</td>
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</tbody>
</table>
Comparison with Dry Cutting

- Slots of 14 mm length with Al7075 were machined; axial depth of cut: 200 µm
- Peak-to-valley forces averaged over 100 revolutions
- Edge radius: ~ 2 µm; Minimum chip thickness: ~ 0.8 µm
- At low feedrate (ploughing regime), tool failed after cutting eight slots with dry cutting
  - With atomized cutting fluid, was able to cut more than 50 slots
- Lower forces with atomized cutting fluids at both feedrates
Comparison with Flood Cooling

- Drops of cutting fluid applied to the cutting area, resembling flood cooling
  - Generated chips are so small, they cluster around the cutting zone due to surface tension of larger drops and essentially zero fluid velocity
- Photos taken after cutting 3 and 27 slots
- The chip cluster increases chances of leaving chip adhered to the machine surface and accelerating tool wear.

![Clustered Chips](image1)
![Micro-End Mill](image2)
![Workpiece](image3)

*After cutting 3 slots*

*After cutting 27 slots*
Summary

1. A three-dimensional fluid dynamic model of particle motion that includes the action of hydrodynamic, electrostatic, and Brownian motion forces was developed to predict flux behavior in membranes.

2. It was shown that partial blocking within a three-dimensional single-passageway pore geometry allows flow to continue though partially blocked pores because they do not become completely sealed.

3. Through the re-design of membranes and re-formulation of fluids microfiltration of MWFs can see higher productivity and therefore greater acceptance in the industrial landscape.

4. Porous media modeling for depth filtration can use the CFD to model fouling of irregularly shaped depth filter pores by irregularly shaped contaminants.

5. A need for right MWFs for micromachining applications.
Thank You

Questions?
Interpretation of Results

Stage One

- Aggregates form and deposit on the membrane and in the pores.
- Causes pore constriction/partial pore blocking.

Stage Two

- Aggregate build-up and blocking.
- Layer of aggregates builds up on the membrane surface.
Fouling Through Aggregation

- Particle size measurements were taken for both the feed and permeate during a 500 nm pore size membrane run.
- In the feed stream a power-law distribution developed
  - Particles reached sizes up to 540 nm after 2000min.
- No particles larger than 65 nm were found in permeate.
Modeling of Membrane Fouling

First semi-synthetic MWF microfiltration model was developed by Zhao et al. [2005].

Created for a dead-end system
   – Does not allow for re-suspension/pore unblocking

Based on an ideal pore and particle geometry

Average particle size of micro-emulsions tested is between 19 nm and 30 nm.

Average pore size varied from 200 nm to 500 nm.
Modeling of Membrane Fouling

Zhao et al. [2005] model is a 3-stage, experimentally fit, model for membrane fouling by a semi-synthetic MWF

- Internal pore constriction
- External pore blocking
- Surface film formation
Modeling of Membrane Fouling

- Semi-Synthetics are shown to foul even in the absence of contaminants (Zhao et al., 2005).
- It appears that particles an order of magnitude smaller than the pores are fouling the membranes.
- Could happen through MWF micro-emulsion aggregation (Menniti et al.)
Sieving Model

- Developed by Starov et al. [2002]
- Determines membrane flux as a function of particle and pore size distributions
- Based on dead-end filtration of polydisperse spheres.
- Only takes into consideration pore blocking.

Fig. 1. Schematic presentation of the microfiltration process: 1. particle adheres to the membrane surface; 2. particle blocking a small pore; 3. small particle goes through a pore; and 4. particle will block the pore.
Pore-Level Fouling Modeling

- Some investigation into particle-pore interactions have focused on the pore level
  - Bowen et al. 1998, 1999, 2002
  - Kim et al. 2003, 2004

- Computational Fluid Dynamics (CFD) models were based on:
  - Ideal cylindrical pore
  - Ideal spherical particle
Fouling Mitigation

Most fouling mitigation research has focused on mechanical methods.
- Turbulence enhancers
- Backpulsing, etc.

Less work has been done on reformulating MWFs.
- Gilmer et al. (2005) reformulated a synthetic MWF.
- Zhao et al. (2007) reformulated a semi-synthetic based on surfactant adsorption.
Membrane Flux Decline

- Fouling causes significant decreases in the level of MWF flux through the system.
- Different types of membranes and fluids have different flux decline curves.

800 nm pore size alumina membrane with uncontaminated Castrol 6519
Effect of Water Phase Surface Tension and Viscosity on Metalworking Fluid Functionality
(Peter Bittorf)

Objective

Develop a better understanding of the specific nature of the relationships between surface tension and viscosity of a MWF and its effectiveness in reducing cutting temperatures and forces.

Approach

Conduct and analyze statistically – designed experiments.
Surface Tension Fluids

- Three fluids will be used in the experiments
  - **DI Water**: Control fluid
  - **Glycol Ether** (*Dowanol PnP)*: Chosen because of ability to reduce surface tension with relatively small concentrations – thus ensuring other DI water properties were held constant
  - **Nonionic Surfactants** (*Neodol 91-6 and 91-8)*: Chosen because they are water soluble and stable
Chemical Concentrations and Surface Tension Values

All surface tension values are measured at 25°C

**DI water surface tension at 25 °C – 72 mN/m**

**Range of surface tension values was fairly wide, but somewhat constrained by chemicals used (29 – 62 mN/m)**

---

### Surfactants

#### Neodol 91-6

<table>
<thead>
<tr>
<th>% Concentration in Deionized Water</th>
<th>Surface Tension (mN/m)</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001%</td>
<td>62</td>
<td>N1</td>
</tr>
<tr>
<td>0.001%</td>
<td>53</td>
<td>N2</td>
</tr>
<tr>
<td>0.01%</td>
<td>33</td>
<td>N3</td>
</tr>
<tr>
<td>0.10%</td>
<td>29</td>
<td>N4</td>
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</table>

#### Neodol 91-8

<table>
<thead>
<tr>
<th>% Concentration in Deionized Water</th>
<th>Surface Tension (mN/m)</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001%</td>
<td>54</td>
<td>N5</td>
</tr>
<tr>
<td>0.01%</td>
<td>37</td>
<td>N6</td>
</tr>
<tr>
<td>0.10%</td>
<td>30</td>
<td>N7</td>
</tr>
</tbody>
</table>
Viscosity Fluids

Two fluids will be used in the experiments

- **DI Water**: Control fluid
- **Block copolymer surfactants (Pluronic and UCon)**: Chosen because they are completely soluble in water, also are inversely soluble so a hydrodynamic lubrication layer forms at high temperatures, and have a high cloud point to ensure the hydrodynamic layer does not form prior to machining.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Surface Tension (mN/m) @ 25 °C, 0.1% aqueous</th>
<th>Viscosity (cP) @ 25 °C, 2% Concentration in DI Water</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pluronic L10</td>
<td>41</td>
<td>1.191</td>
<td>P1</td>
</tr>
<tr>
<td>Pluronic L64</td>
<td>43</td>
<td>1.271</td>
<td>P2</td>
</tr>
<tr>
<td>Pluronic 31R1</td>
<td>34</td>
<td>1.208</td>
<td>P3</td>
</tr>
<tr>
<td>UCON 50-HB-660</td>
<td>38</td>
<td>1.259</td>
<td>U1</td>
</tr>
</tbody>
</table>

DI Water Viscosity @ 25 °C = 0.89 cP
Test Set-Up

- **Equipment**: Mori-Seiki TV-30 Light Milling/Drilling/Tapping Machine
- **Drill**: 12.7 mm diameter HSS oil hole drill
- **Workpiece**: 25.4 mm diameter by 63.5 mm long blank of 1018 steel with a 19.05 mm diameter by 19.05 mm deep counterbore (fluid reservoir)
- **Process Parameters**:
  - 12.7 mm deep holes
  - Speed: 30.32 m/min
  - Feed: 135 mm/min
  - Six replicate holes in a randomized order with each fluid
  - Torque and thrust recorded with a Kistler dynamometer
  - Temperature measured by t-type thermocouple in oil hole pathway (approximately 0.5 mm below flank face)
  - Temperature signal transferred from drill to signal conditioner with slip ring
Results suggest that reductions in surface tension lead to reduction in cutting temperatures.
Friction Reducing Properties of Glycol Ether Solutions

No statistical evidence of force reduction with glycol ether solutions, which indicates that they may have similar lubrication properties to DI water.
Illustrate that sizeable surface tension reductions lead to reductions in cutting temperature – modest surface tension reductions may not be as effective.
Reduced forces observed with varying viscosities demonstrate friction reducing effect of increased viscosity

Statistical analysis indicates that all viscous solutions were significantly different from DI water but not different from each other
Conclusions

Based upon this study once the surface tension value was at or below approximately 35 mN/m statistically significant decreases in temperature were observed.

By increasing the viscosity of the MWF just 0.3 cP above DI water a statistically significant decrease in machining forces was realized.

This result experienced with viscous lubrication indicates the important contributions made to MWF functionality by the hydrodynamic regime and is useful for future formulation considerations.

The findings from this study are important for industrial or custom MWF chemical compositions and concentrations to achieve properties (surface tension and viscosity) that improve functionality.
Atomized Particle Dynamics

- Influencing parameters for droplet impingement dynamics
  - Droplet diameter ($d_o$)
  - Velocity of the incident droplet ($w_o$)
  - Fluid dynamic viscosity ($\mu$),
  - Fluid density ($\rho$)
  - Fluid surface tension ($\sigma$)
  - Thickness of liquid film ($h$) formed on the surface

- Non-dimensional numbers based on normal velocity component, $w_o$
  \[
  We = \frac{\rho w_o^2 d_o}{\sigma}, \quad Re = \frac{\rho w_o d_o}{\mu}, \quad Oh = \frac{\mu}{\sqrt{d_o \sigma \rho}}, \quad h_{nd} = \frac{h}{d_o}
  \]

  **Stick:** $We < 5$, **Rebounding:** $5 < We < 10$
  **Spread:** $5 < We$ & $K < K_c$ or $K_y < K_{yc}$ or $K_m < K_{mc}$
  **Splash:** $K > K_c$ or $K_y < K_{yc}$ or $K_m > K_{mc}$

Applied droplets need to be in the spreading regime to effectively wet the cutting zone.

Identifying Fouling Mechanisms for Flux Decline

- The first step in mitigating fouling is understanding the fouling mechanisms.

- Fouling mechanisms are determined through SEM imaging and flux decline curves.