Joining Techniques for Novel Metal-Polymer Hybrid Heat Exchangers

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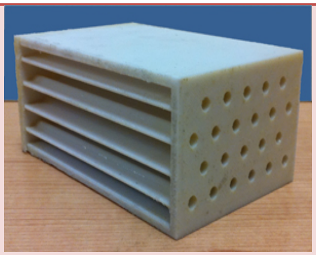
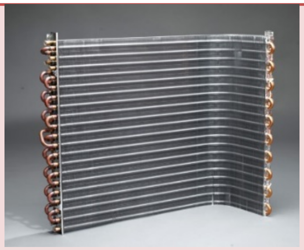
Low temperature heat recovery

~ **50%** of industrial waste heat is < 200 °C

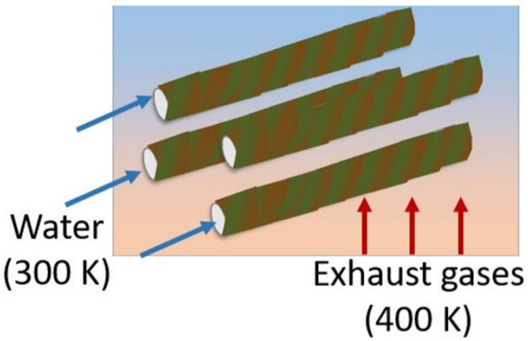
Current low temperature (< 150 °C) waste heat recovery HX

Not viable & payback period > 3 years

	Polymers	**Metal**
Metric	 *Source: Cevallos, TherPES lab, Univ of Maryland*	 *Source: Zhejiang Tongxing Refrigeration Co., Ltd.*
Cost	$	$$$
Corrosion & Fouling	Minimal	Problematic
Thermal Conductivity	Low (~ 0.2 W/m.K)	High (~ 400 W/m.K)
Weight	Low	High

BCS incorporated, 2018; Thekdi, Nimbalkar, Oak Ridge National Lab 2015

Overall Heat Transfer Coefficient (U)



Related Talk:
Design of hybrid metal-polymer heat exchanger for low temperature waste heat recovery
11421, Nov 11, 4:40 PM

Rajagopal et al., IJHMT 2019

<u>Calculation specs:</u>

$t_{wall} = 2.5\text{mm}$,

Fouling resistance $= 0.005\ [\text{m}^2\text{K W}^{-1}]$,

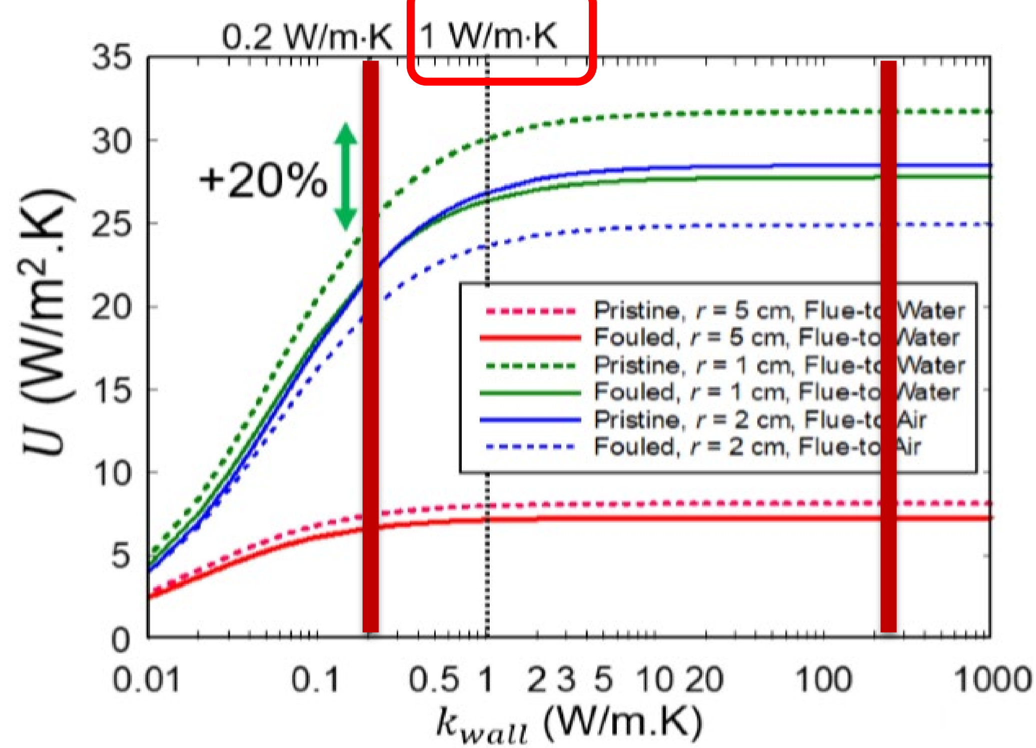
Water flow rate (inner) $= 0.005$ kg/s,

Air flow rate (outer) $\sim 4.7\ \text{m}^3/\text{s}$

1MW waste heat source

$$U = \frac{1}{\dfrac{1}{h_{flue} * A_o} + \dfrac{\ln\dfrac{r_i + t_{wall}}{r_i}}{k_{wall} * 2\pi L} + \dfrac{1}{h_{water} * A_i}}$$

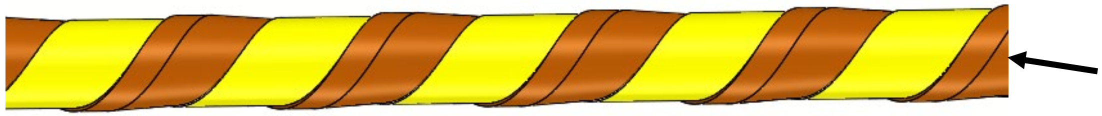
For t = 2.5mm



Overall U across a certain cross-flow HX

Design of metal-polymer hybrid tubes

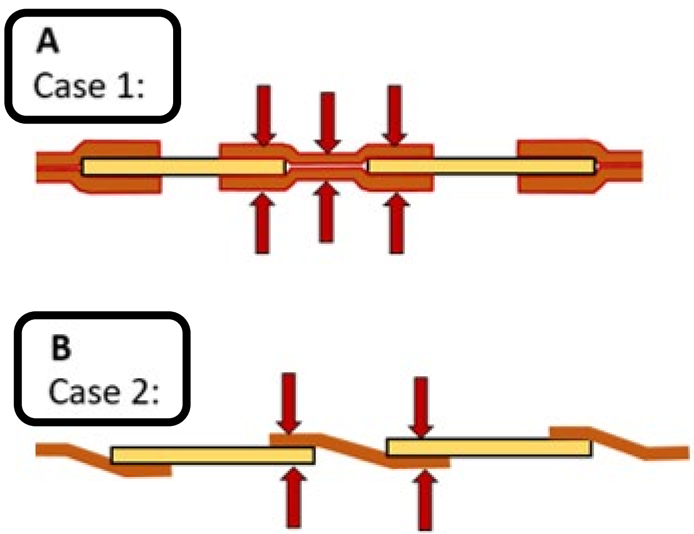
Material choices
Metal: **Cu**, Al
Polymer: **Kapton** (Polyimides)

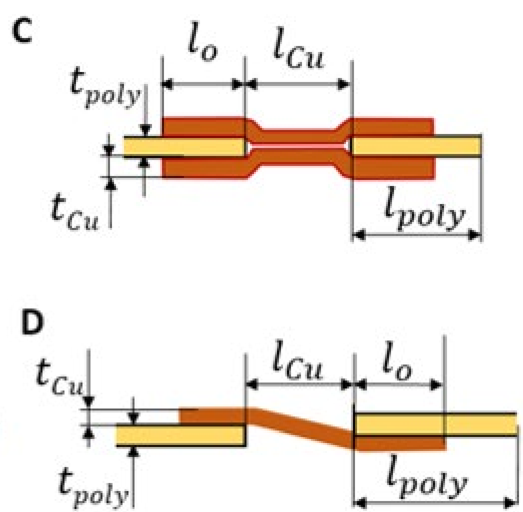


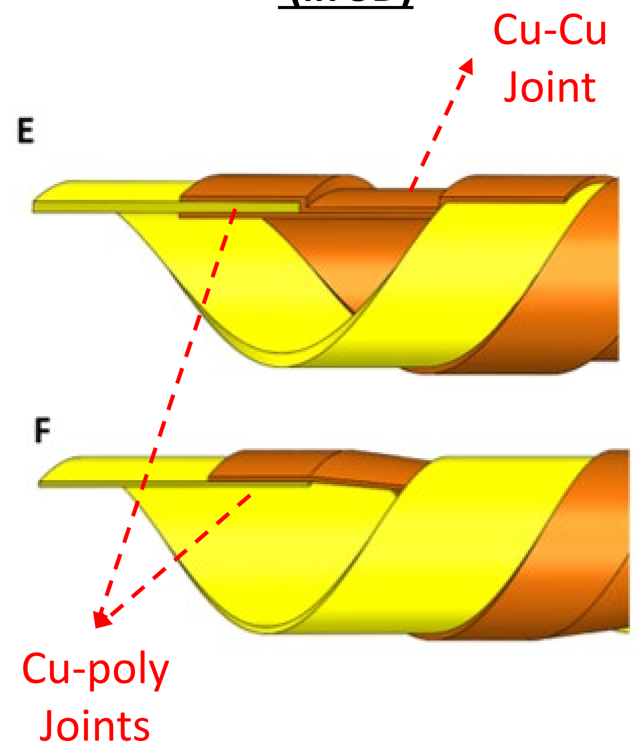
Top wall cross section

Wall unit cell

Cut section of tubes (in 3D)



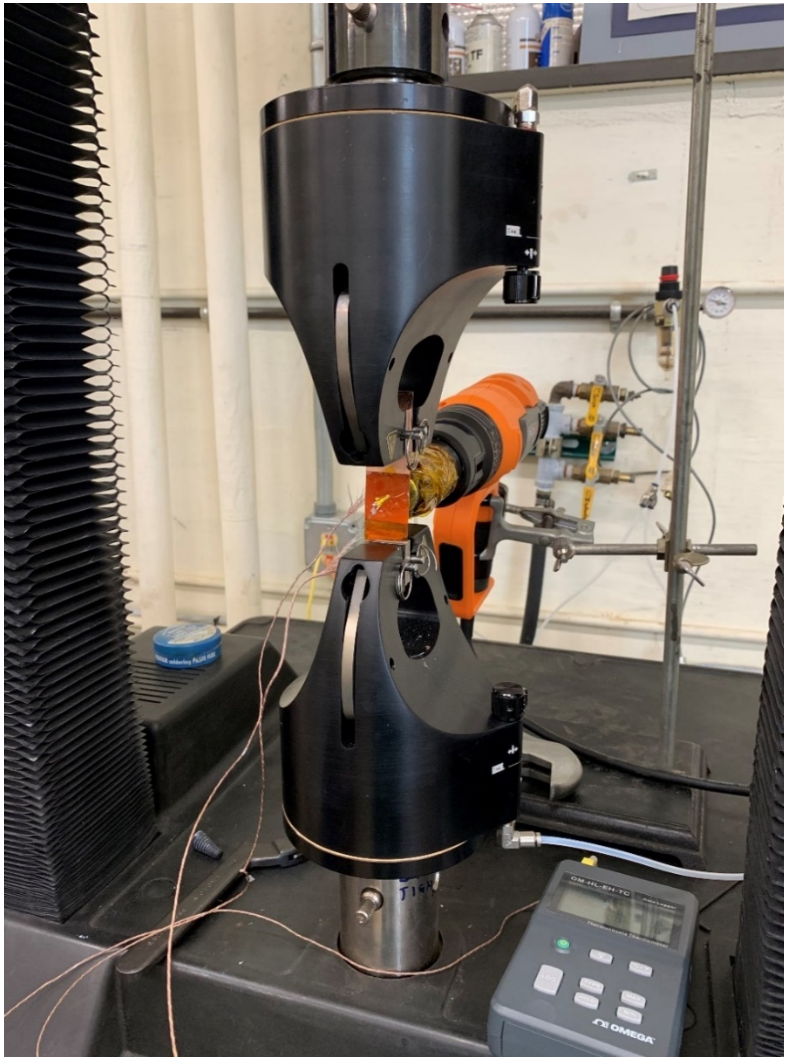


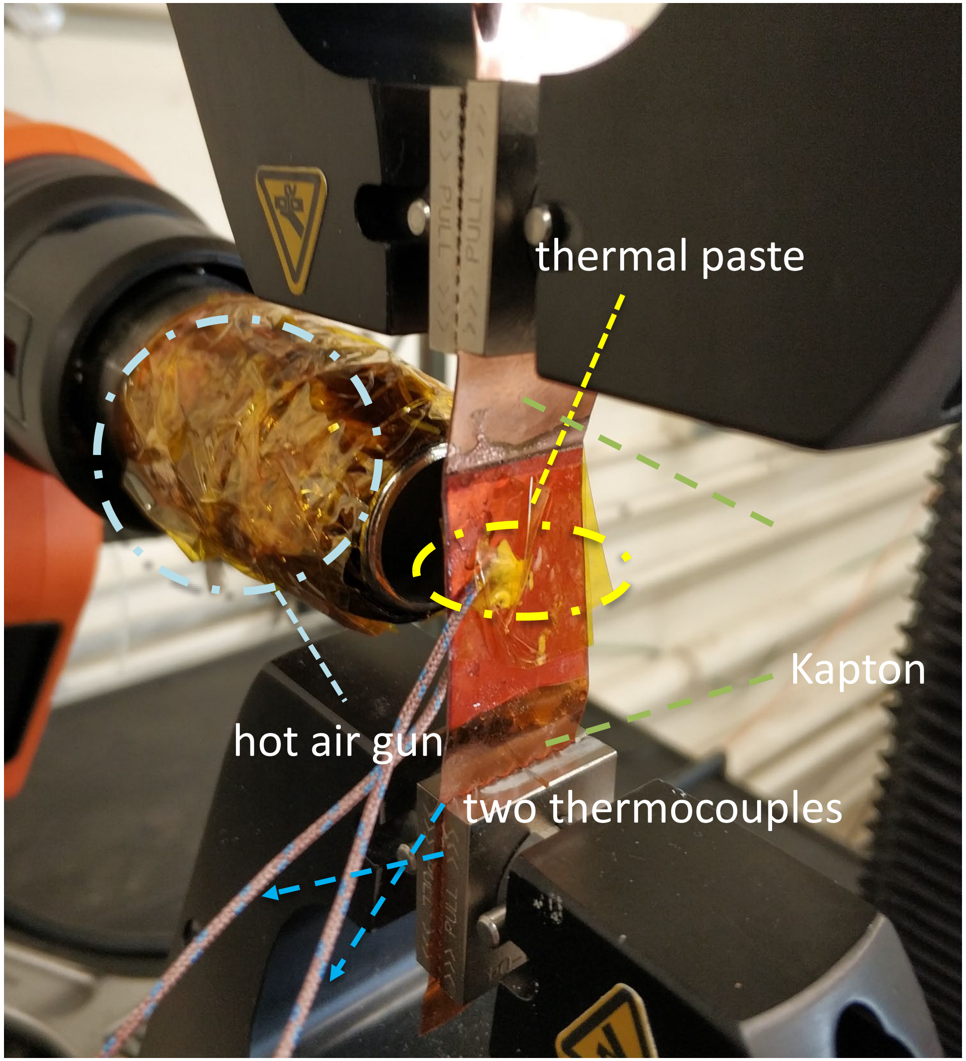


~ **50% savings in metal costs**

**US patent application – in progress*

Joints characterization at testing facility

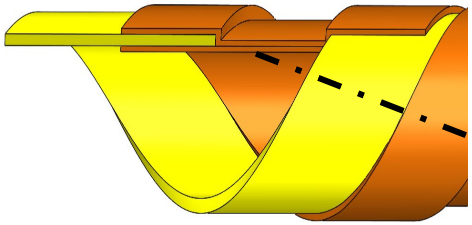




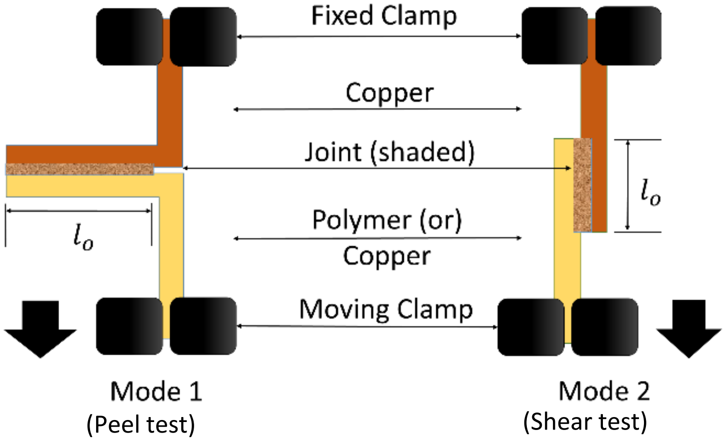
Universal Testing Machine

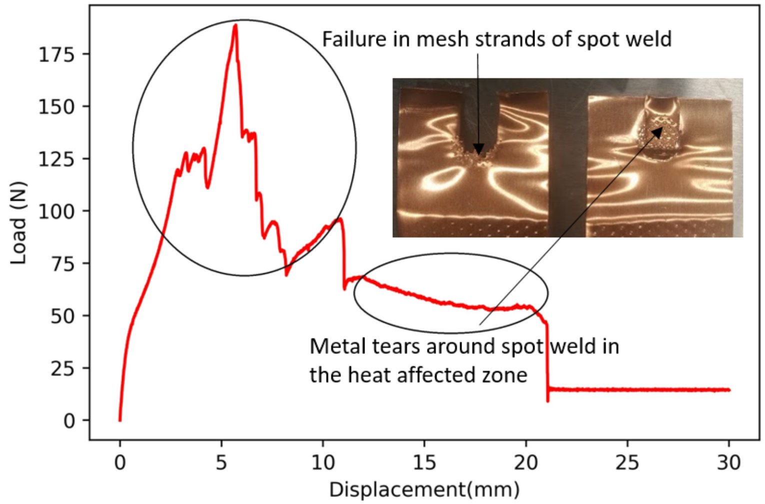
Ultrasonic welding (Cu + Cu) - load curves

Introduction | HX Design | **Characterization** | Mfg. Setup | Summary



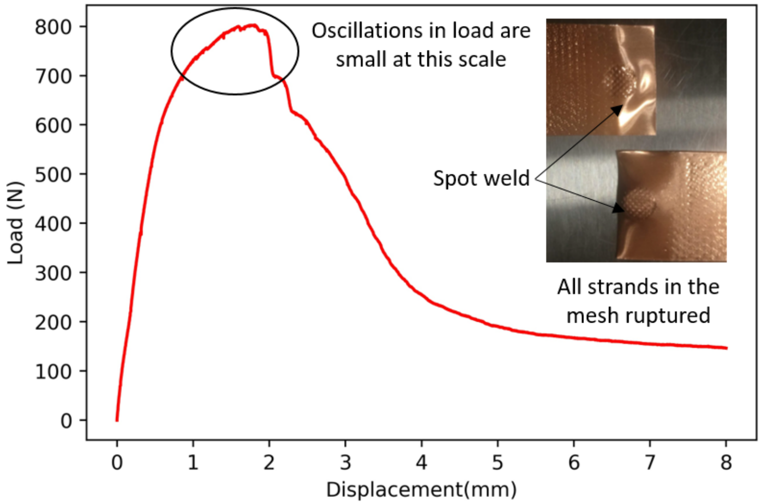
Ultrasonic weld joints b/w Copper and Copper





Peel Test

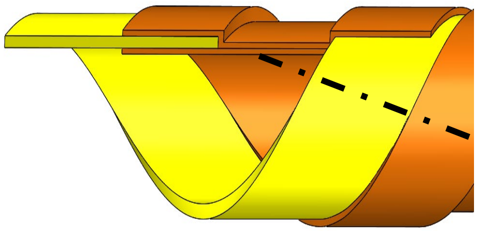
Results @ 25°C only



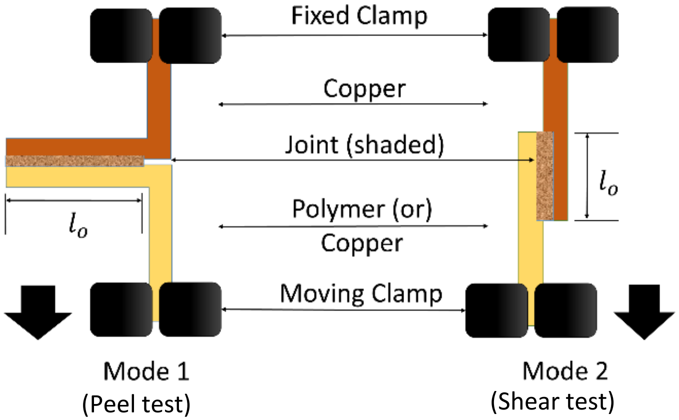
Shear Test

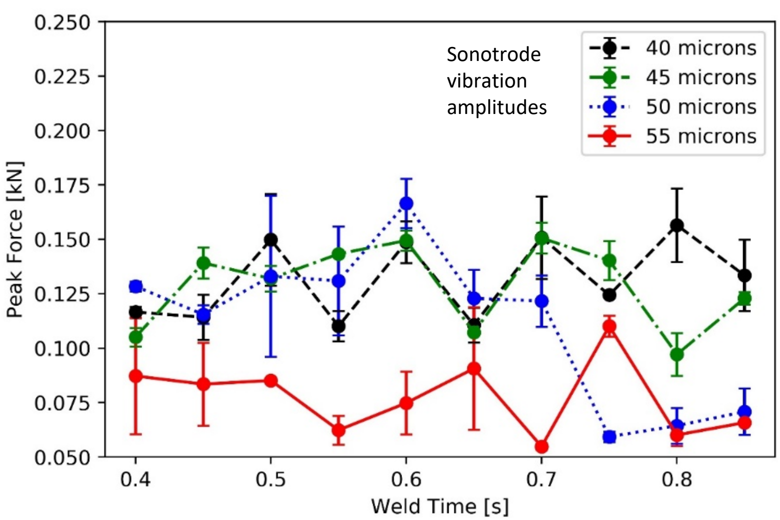
Illustrative Curves

Ultrasonic welding (Cu + Cu) - test results



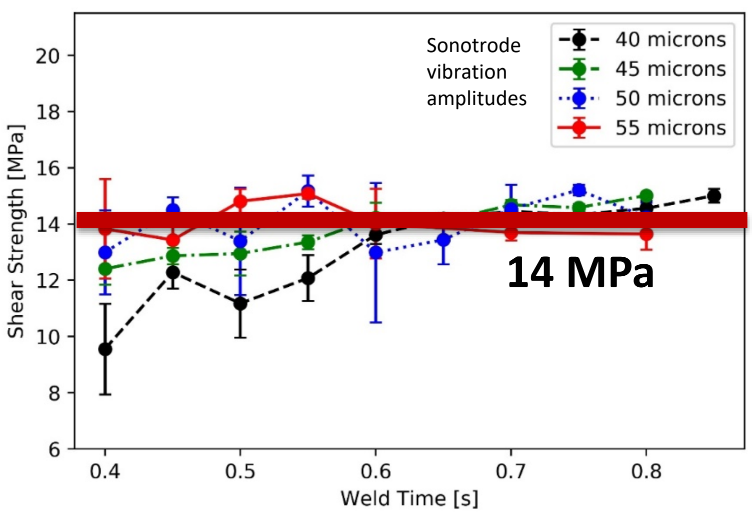
Ultrasonic weld joints b/w Copper and Copper





Peel Test

Results @ 25°C only

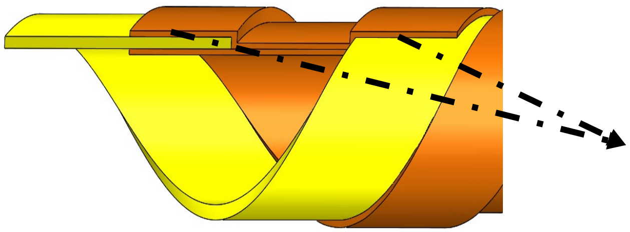


Shear Test

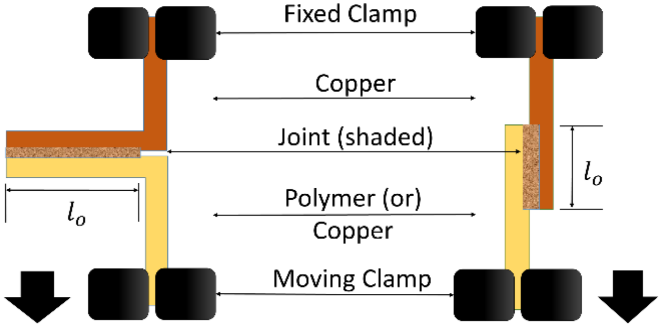
Sample: ~ 10 mil (250 µm) Copper + ~ 10 mil Copper

10 repetitions per joint

Adhesive joints (Cu + poly) - load curves

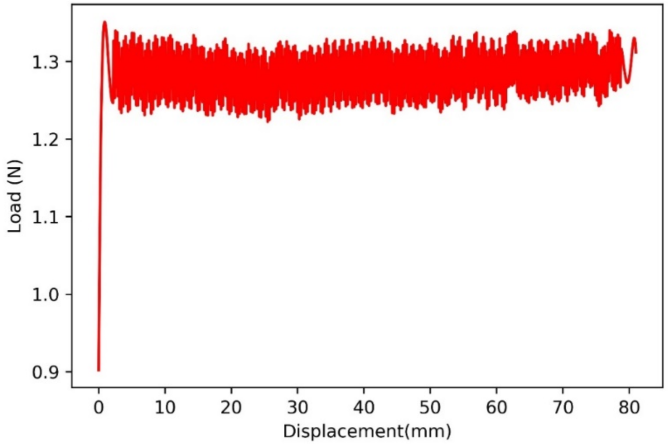


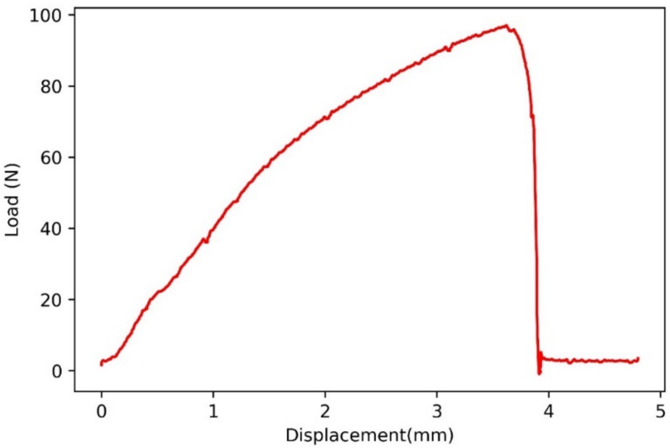
Adhesive joints b/w
Copper and **Polymer**



Peel Test

(ASTM D1876)



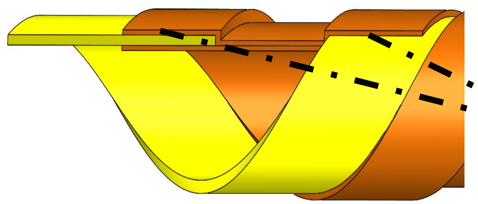


Shear Test

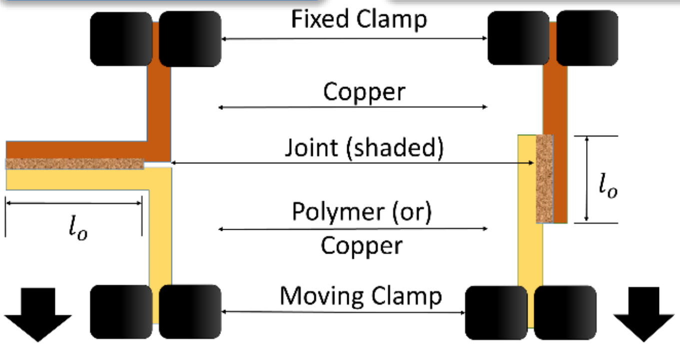
(ASTM D3165)

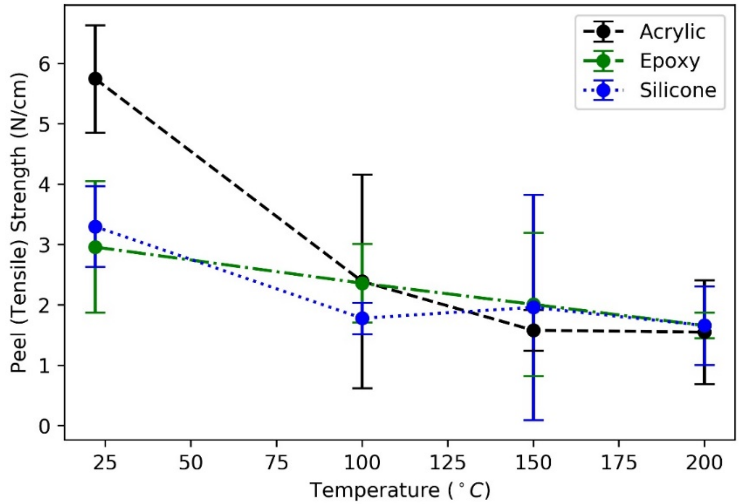
Illustrative Curves

Adhesive joints (Cu + poly) - test results

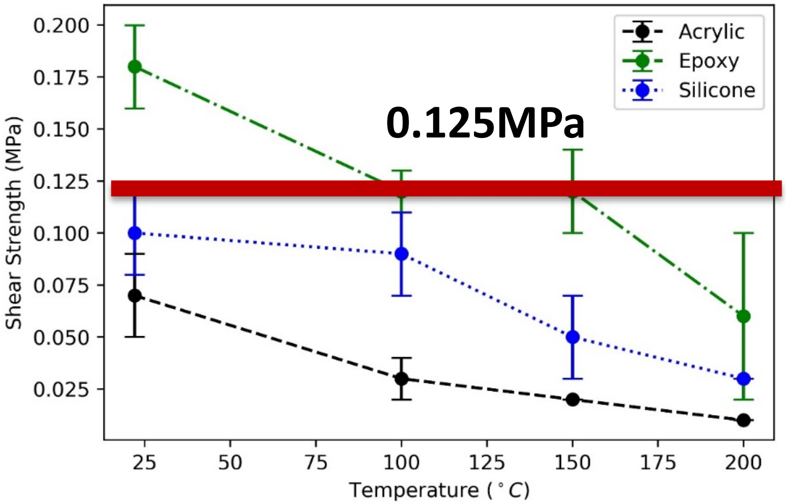


Adhesive joints b/w
Copper and **Polymer**





Peel Test
(ASTM D1876)



Shear Test
(ASTM D3165)

Sample: ~ 1mil (25µm) Copper + ~ 1mil Adhesive + ~ 1mil Kapton

5 repetitions per joint

Takeaways: characterization of joints

Adhesives (Cu + poly):

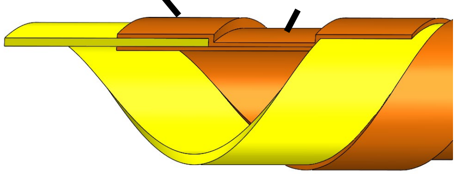
- Weak link
- Tough to join Copper + Kapton
- Temperature ↑ → Bond Strength ↓

Ultrasonic Welding (Cu + Cu):

- Kapton + Cu **not** possible
- Science not yet fully understood
- Empirical expts. to get best parameter set

Adhesive Shear Strength:
~ **0.13 MPa**
(Cu + poly)

USW Shear Strength:
~ **14 MPa**
(Only Cu + Cu)



Recent testing (after acceptance of this paper)

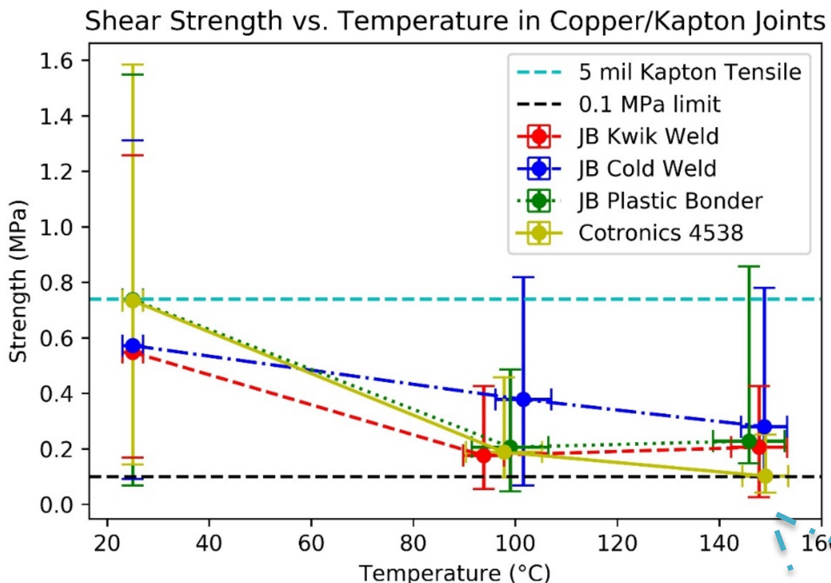
Epoxy: good alternative joint for Cu/Poly.

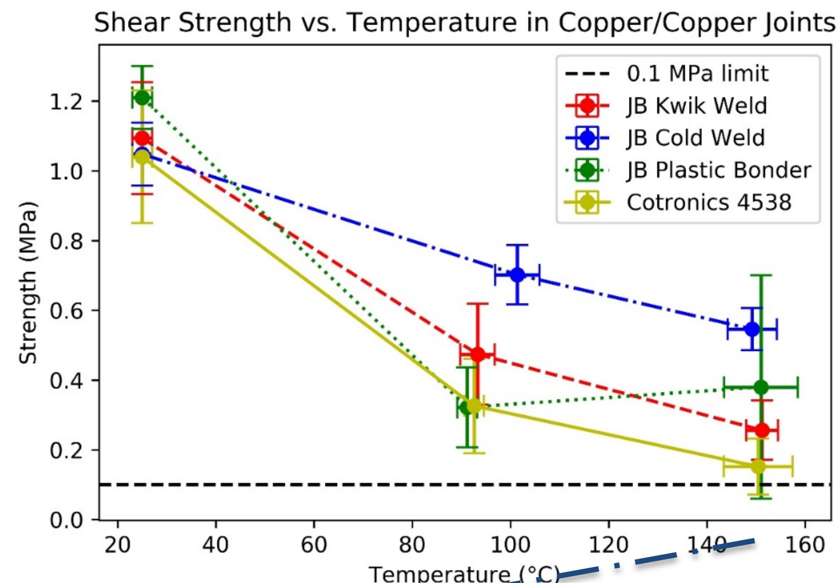
How does it work for Cu/Cu?

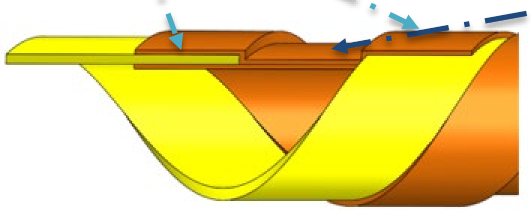
Copper/Kapton Joints

5 repetitions per joint

Copper/Copper Joints







Target Operational Temperature = **150 °C**

Epoxy Shear Strength:

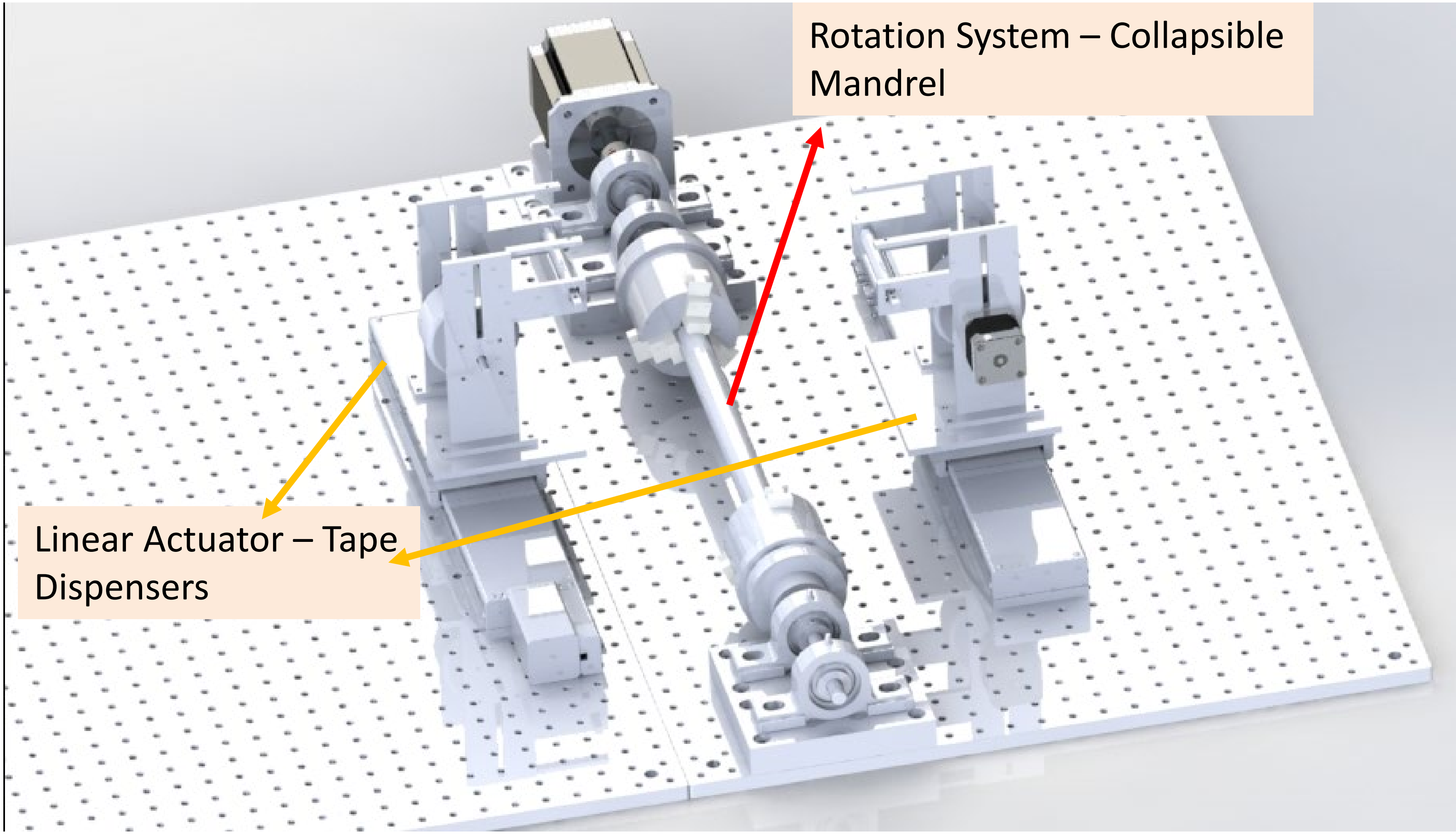
~ 0.35 MPa (Cu/poly)

~ 0.55 MPa (Cu/Cu)

*** Not published in this paper**

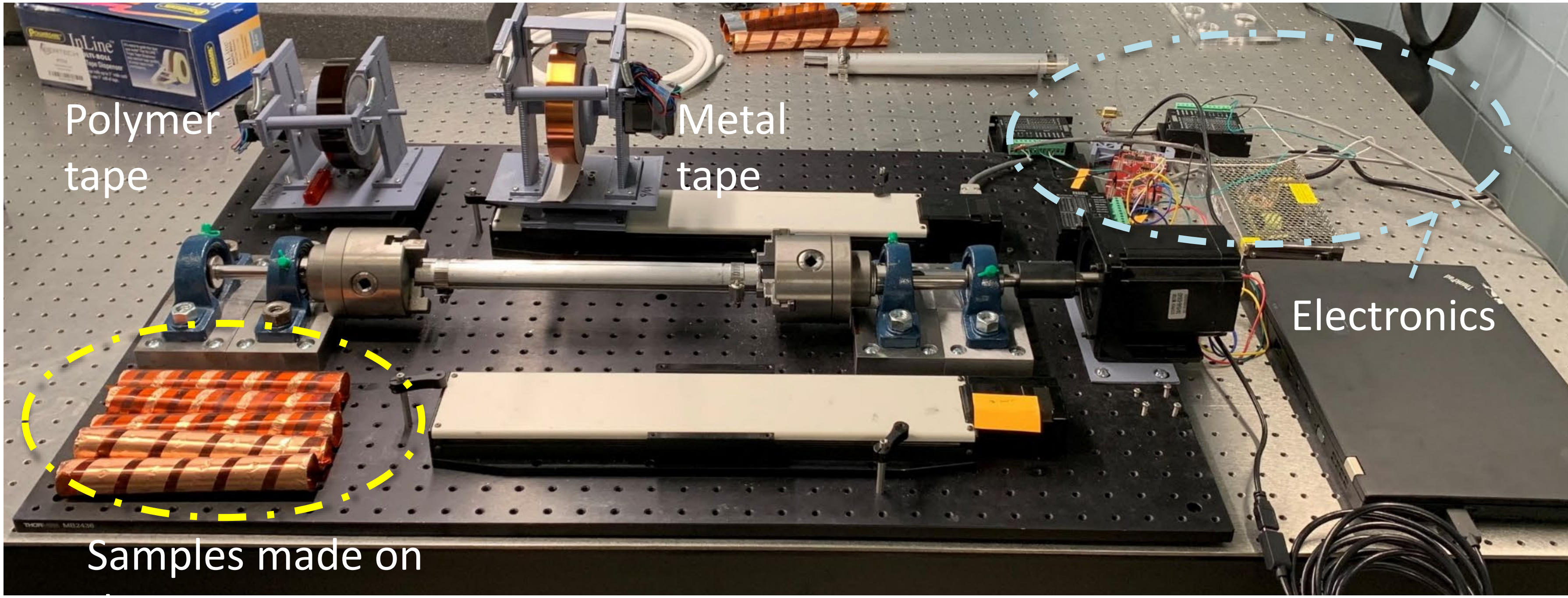
Manufacturing Setup - CAD

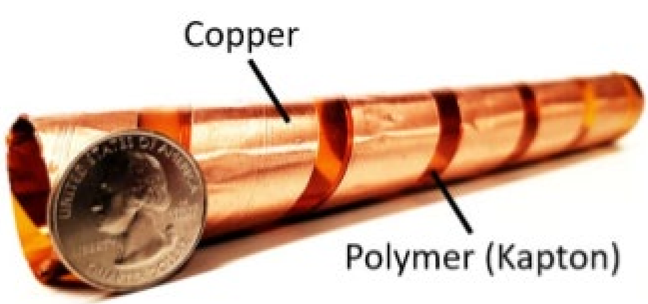
Built in-house at UIUC



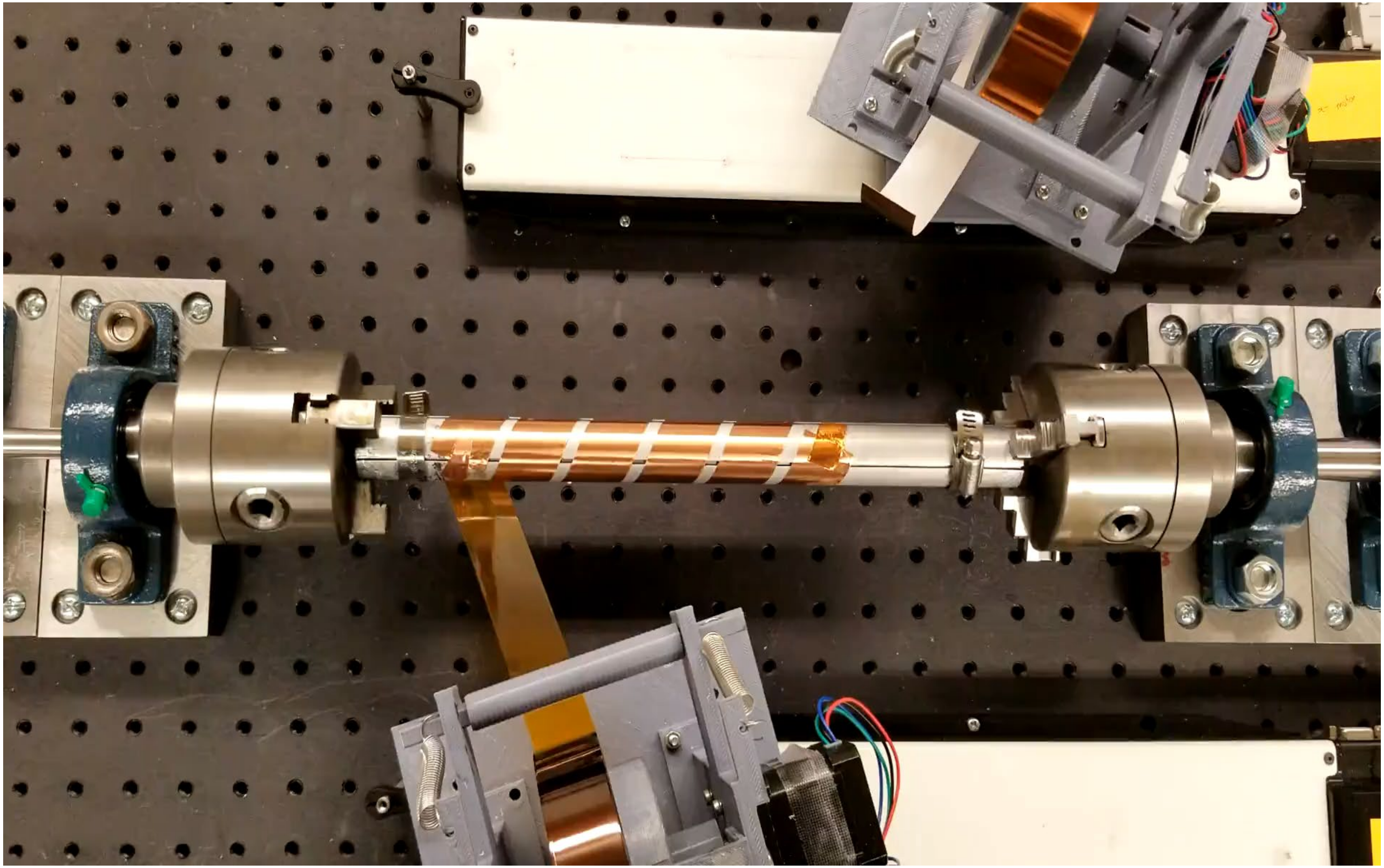
*Adhesive dispensing, motor driver electronics **not** shown

Manufacturing Setup – Actual setup



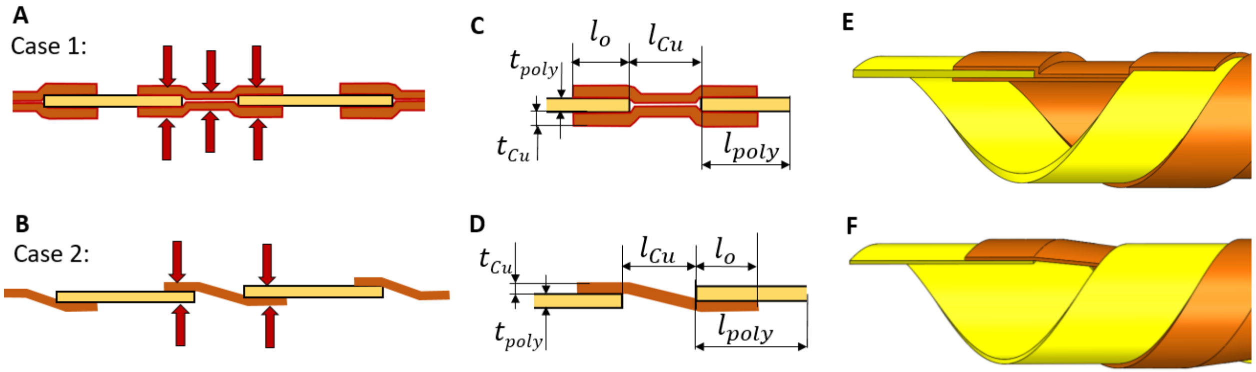


Working Video – Helical Tape Laying Process

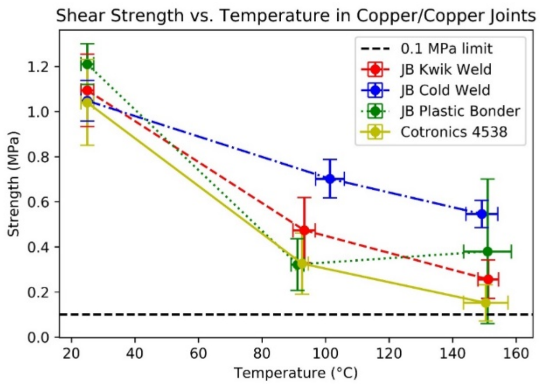


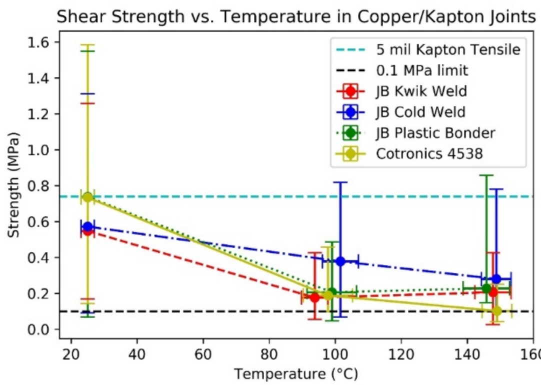
Summary

Design



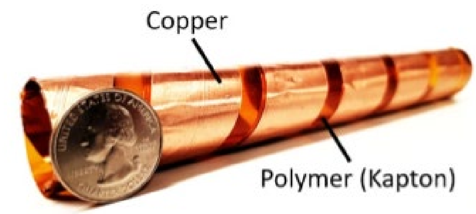
Testing Joints





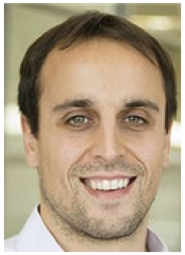
Epoxy joints are promising

Prototype

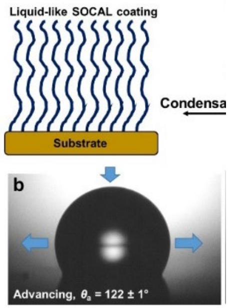


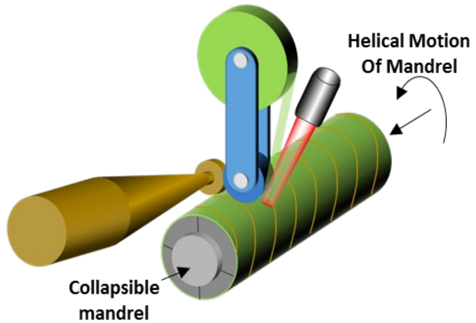
Acknowledgements

PI: Prof. Sanjiv Sinha



Prof. Nenad Miljkovic

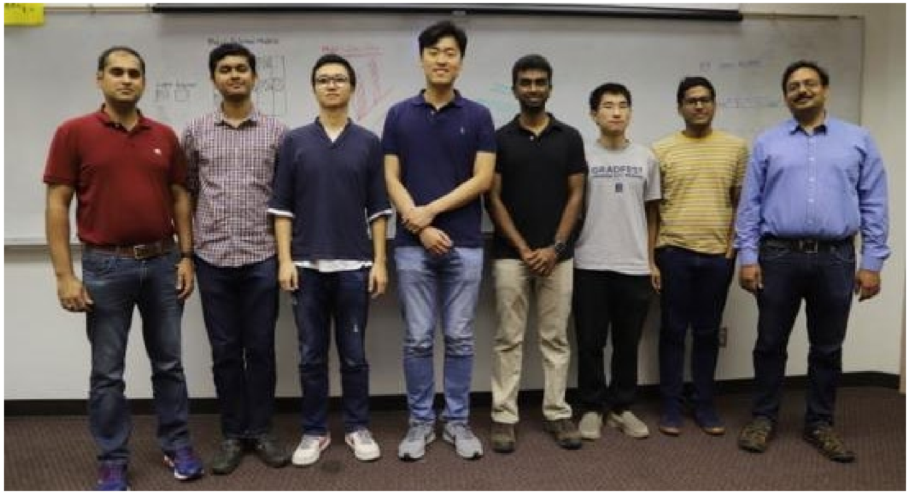




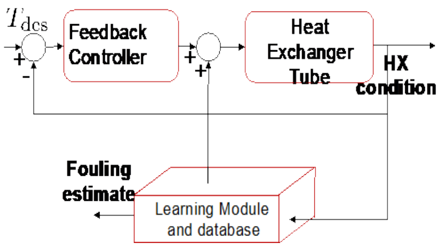
DOE Award No. DE-EE0008312

Prof. Placid Ferreira

Prof. Chenhui Shao



Our team

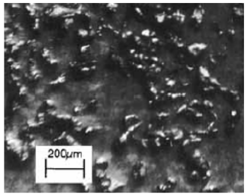


Prof. Srinivasa Salapaka

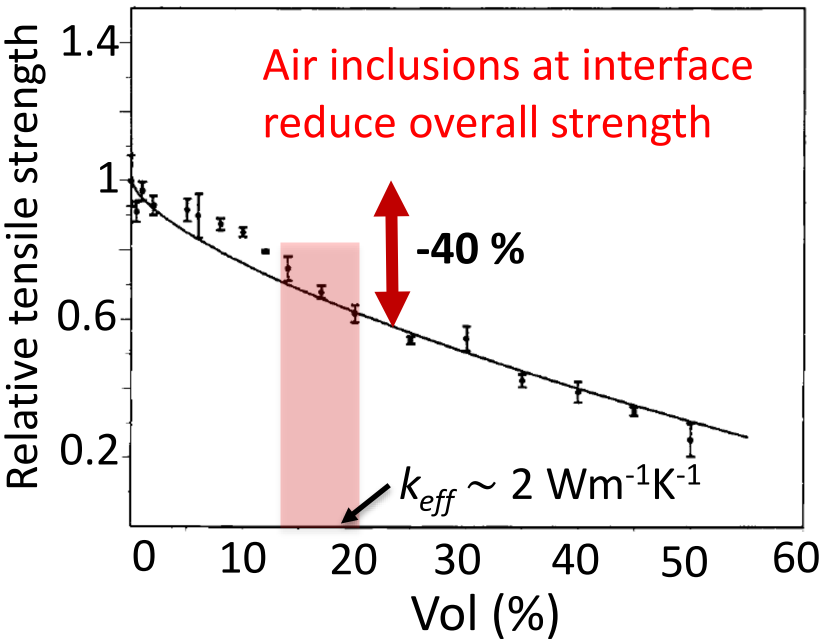
Appendix

Enhancing polymers

Tavman, I.H., *J. App. Poly. Sci.* (1996)

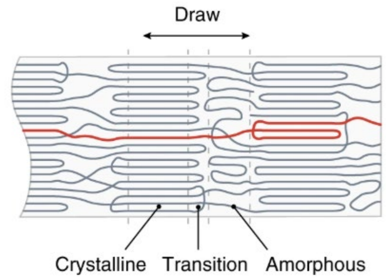


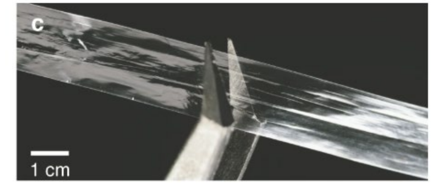
Aluminum powders in HDPE



Xu et al., *Nat. Comms.* (2019)

Stretched/ aligned polymers





Good heat spreaders

$k_{in\text{-}plane} \sim 62\text{-}\ 200\ Wm^{-1}K^{-1}$

Poor transverse thermal conductivity

Transverse elastic moduli 15 %

Maximum operating pressure for polymer pipes ~ 150 psi

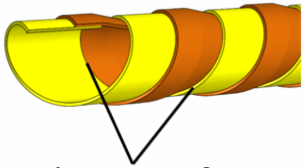
Objective:

- High transverse *heat transfer* ($k_{eff} \sim 1\ Wm^{-1}K^{-1}$)
- Have higher *operating pressures* (~ 150 psi)

- Reduce *material* costs: hybrid metal-polymer
- Ease of *manufacturing scalability*

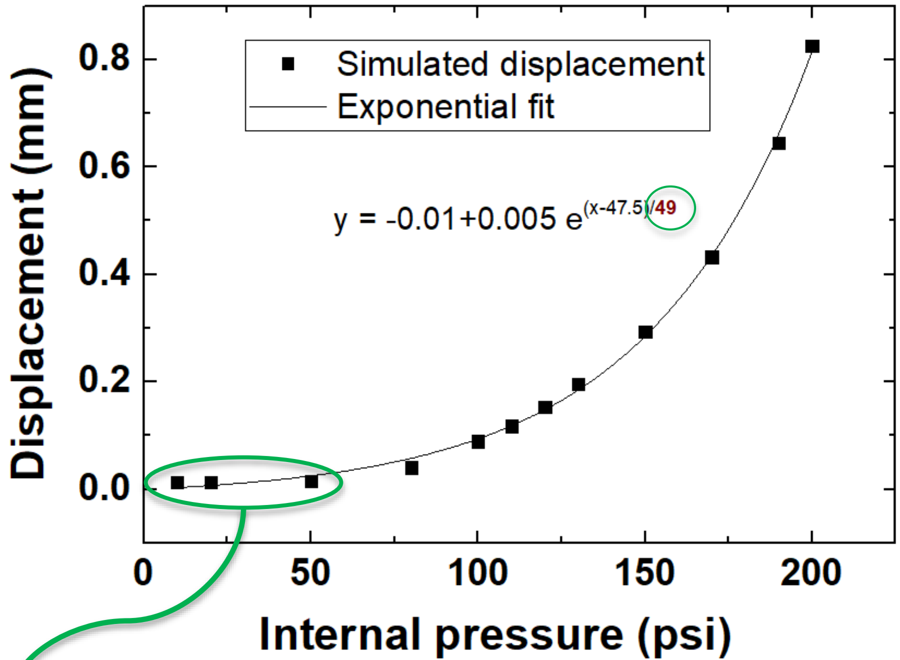
Why shear strength > 0.1 MPa is enough?

At high internal pressures, the joint surfaces move, causing delamination:



Simulated using cohesive zone modelling (CZM)

For a 0.1 MPa joint shear & tensile strength:



Safe maximum internal pressure ~ 50 psi (0.3 MPa),

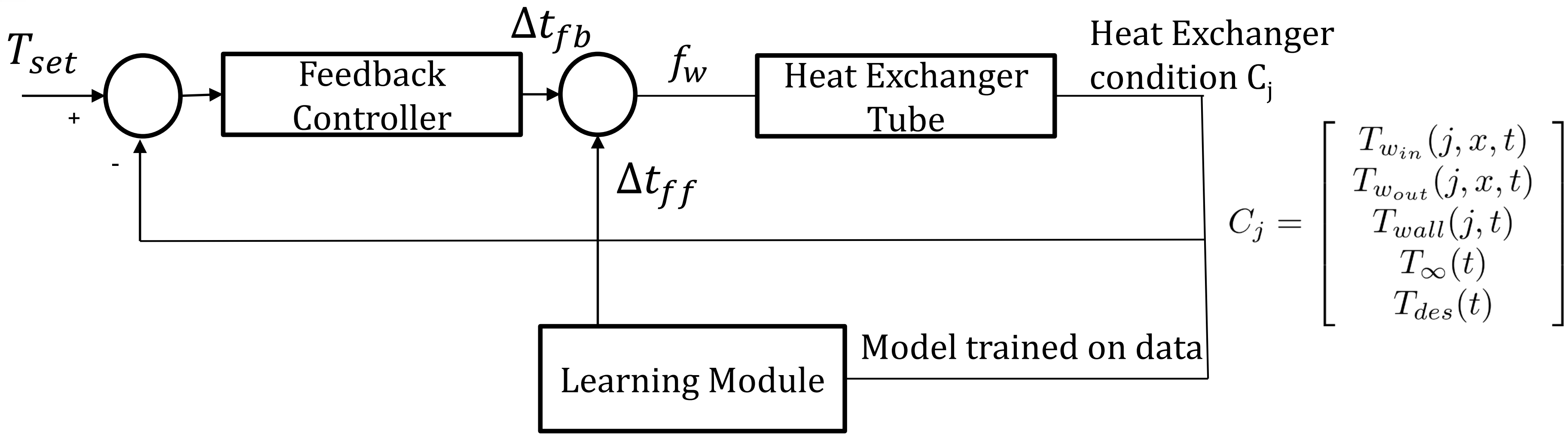
Takeaway

Joint shear/tensile strength of ~**0.1 MPa** is enough for a **50 psi** water flow

Further, we anticipate only a maximum of **3-5 psi** absolute pressure during parallel operation

Glimpses of related work

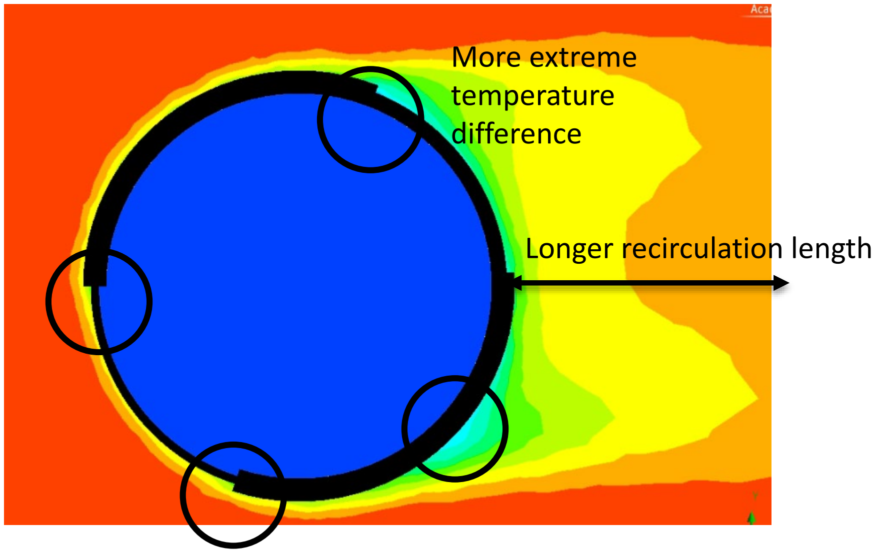
Controls & Health Monitoring



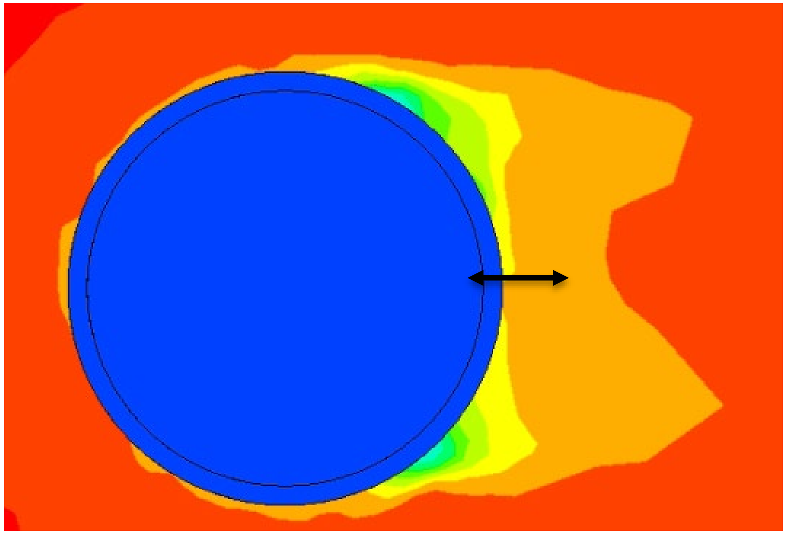
- **Objective**- Design controls architecture for low cost waste heat recovery heat exchangers:
  - typically result in reference tracking/regulation problems
  - e.g. regulate flue gas outlet temperature (T_{fout}) by control of flow rate (f_w)
- **Key Challenges**- Unmodeled dynamics, large uncertainties and noise
  - uncertainties in flue gas conditions (e.g. flow rates and temperatures)
  - unknown/complex system dynamics
- **Approach**- Learn from historical data
  - Learn steady state controller operating points (slow-time scale)
  - Real-time feedback controller for accurate temperature regulation

Comparison of Flow Passing Two Tubes

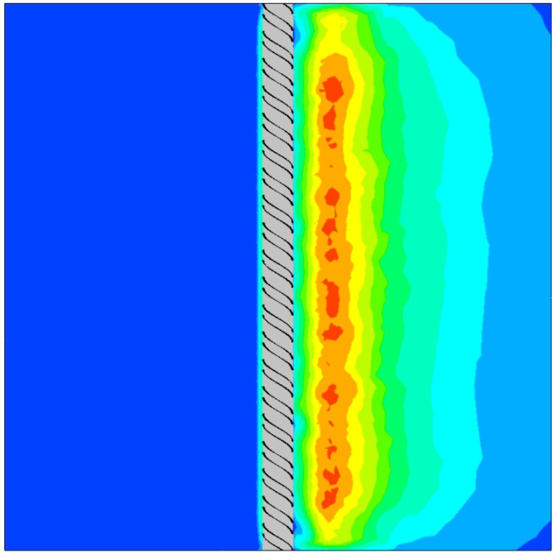
Temperature contour / R2R tube



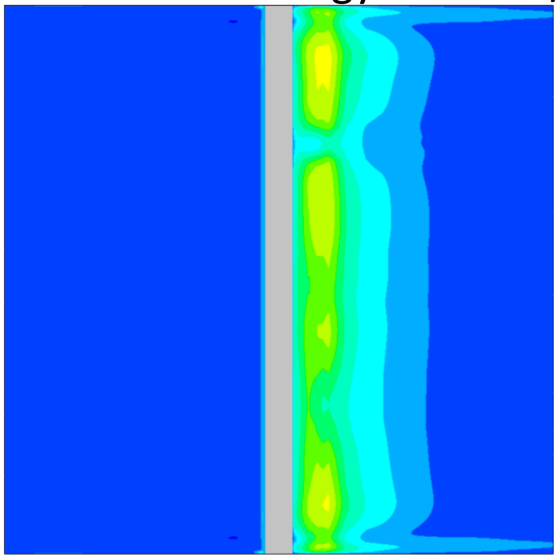
Temperature contour / Smooth tube



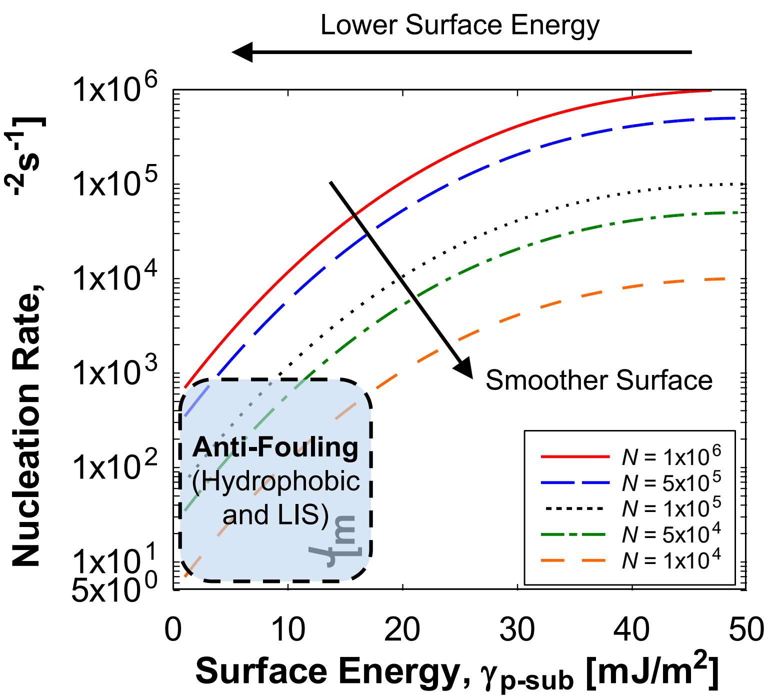
Turbulence kinetic energy contour / R2R



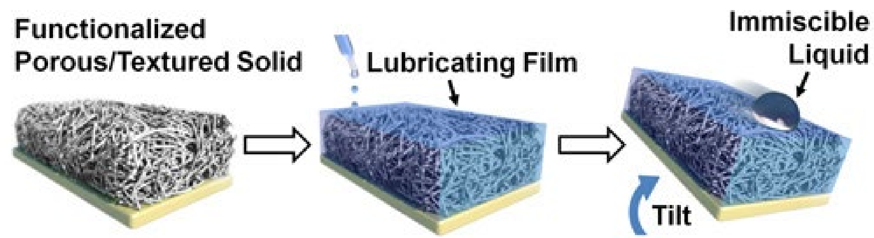
Turbulence kinetic energy contour / Smooth



Anti-fouling Coatings



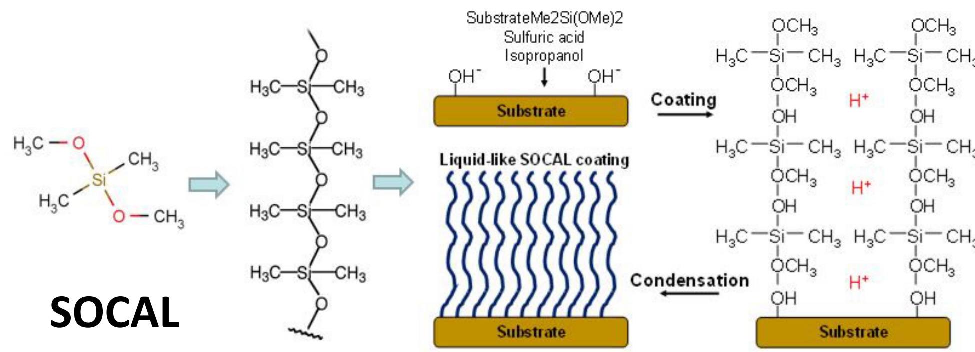
SLIPS or LIS



Classical Nucleation Theory

$$R = \boxed{N_S} Zj\exp\left(\frac{-\Delta G}{k_B T}\right)$$

$$\Delta G = \frac{4}{3}\pi r^3 \Delta g + 4\pi r^2 \boxed{\sigma}$$



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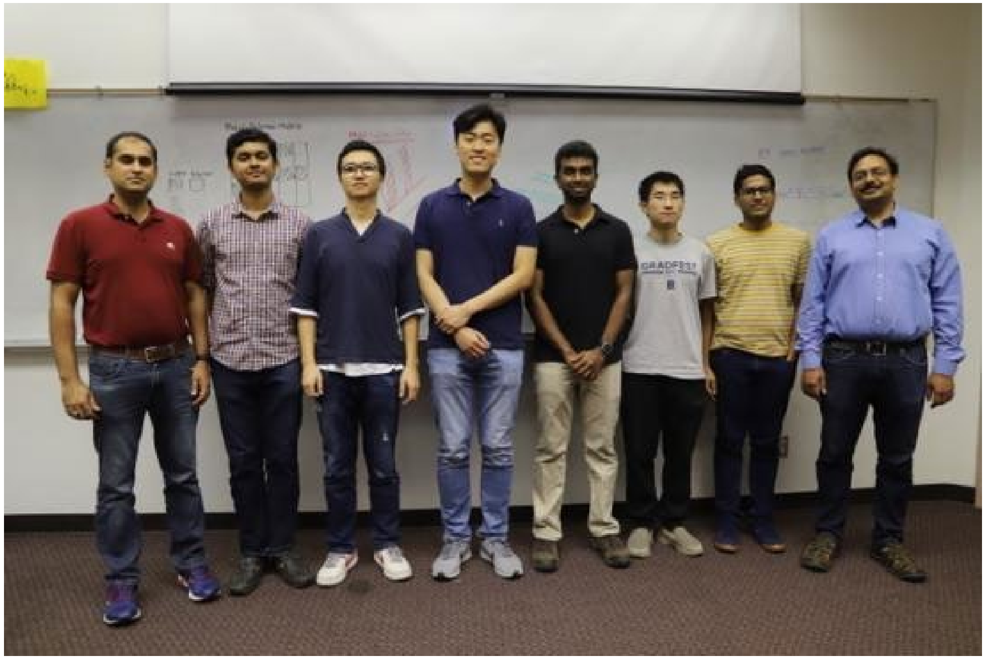
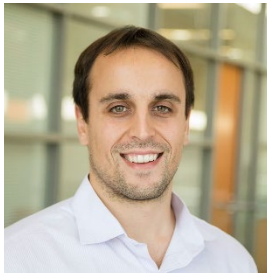
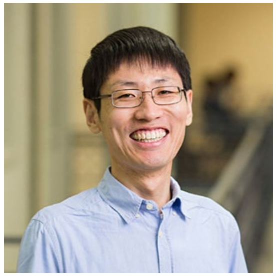
DOE Award No. DE-EE0008312





Dr. Nenad Miljkovic

Dr. Placid Ferreira



Dr. Chenhui Shao

Dr. Srinivasa Salapaka

Other aspects: Controls & health monitoring, HX Simulations,

Dr. Sanjiv Sinha (lead PI)