Novel Patterned Surfaces for Improved Condenser Performance in Power Plants

Project Number: FE0031556
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Project Objectives

The overall aim of the project is to enhance thermoelectric power plant performance through engineered non-wetting condenser surface designs by:

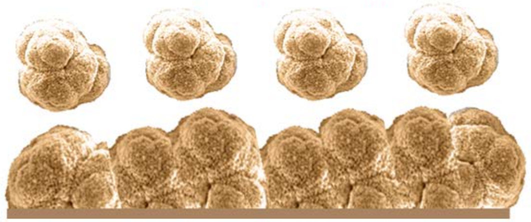
1. promoting dropwise condensation of the steam on the shell side and eliminating flooding of the surface structure by maintaining low droplet adhesion, thus increasing condensation heat transfer;
2. accommodating higher flow rate of cooling water in the tubes for a fixed pressure drop due to reduced drag, thus improving the forced convection heat transfer coefficient; and
3. deterring fouling and corrosion, thereby reducing fouling resistance and improving heat transfer.

The stretch goal is to demonstrate overall condenser effectiveness 50% higher than current systems, while reducing the condenser pressure and improving power plant efficiency.

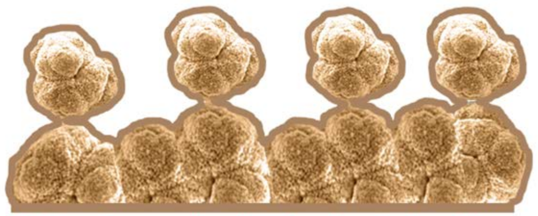
Approach

- Novel patented process for producing superhydrophobic metallic coatings via electrodeposition developed by the PI*.
- Coating could be integrally formed on the base metal substrate, eliminating issues of interfacial failures.
- Electrodeposition is a widely used process in the industry and is scalable.
- The project will apply the process for patterned superhydrophobic surfaces on condenser materials.
- The project will also study liquid infused patterned microstructures to create slippery non-wetting surfaces (SLIPS) on condenser tube materials.

Cauliflower-shaped structures form on the deposit surface when a high overpotential is applied.



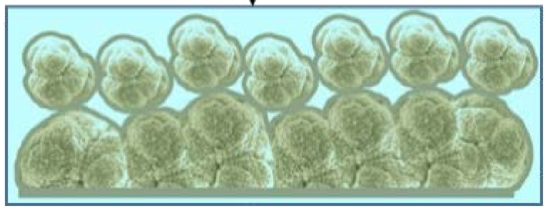
With increasing time or increasing overpotential, the multiscale branches appear on the surface.

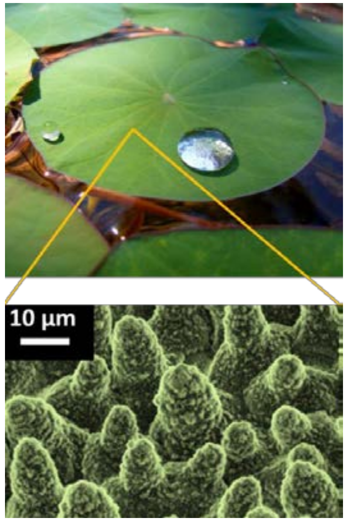


The branches are adhered to the surface by depositing an additional thin layer of metal at a low overpotential for a short time creating a stable superhydrophobic texture.

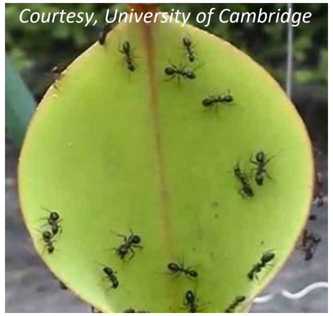
*https://patents.google.com/patent/WO2014127160A2

Dipped in lubricant





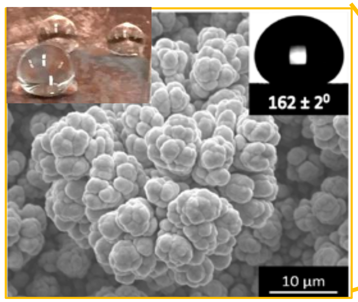
Beilstein J Nanotechnol. 2011; 2: 152–161

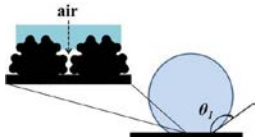


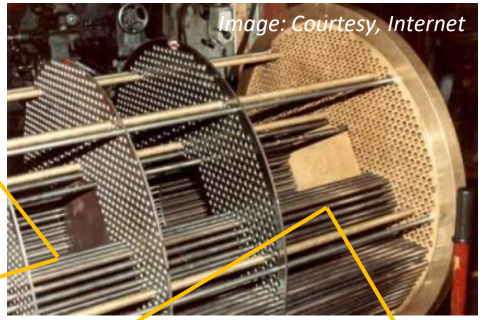
Ants aquaplaning in a pitcher plant– SLIPS in nature

$\theta > 120^{o}$ (hydrophobic)

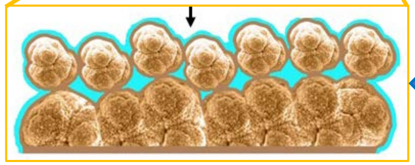
θ







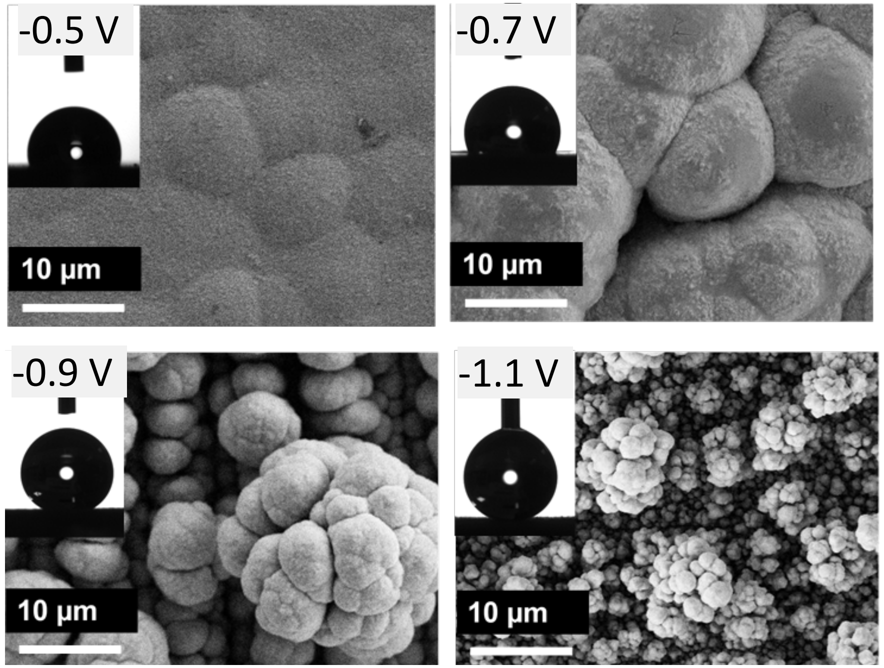
SLIPS on Condenser Tubes

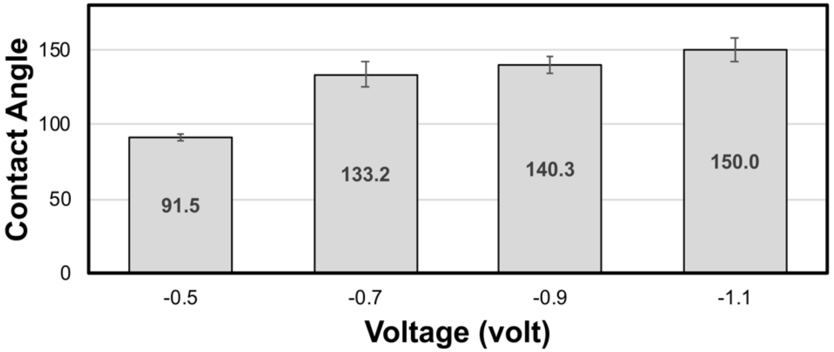


Outline

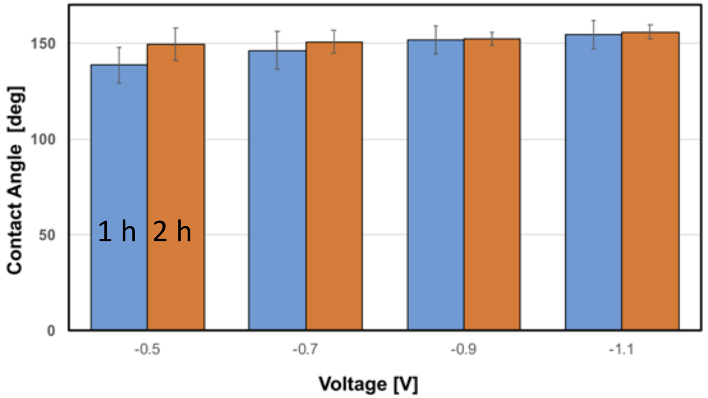
- Fabrication and Process Parameter Identification
- Condensation Heat Transfer
- Corrosion inhibition on non-wetting surfaces

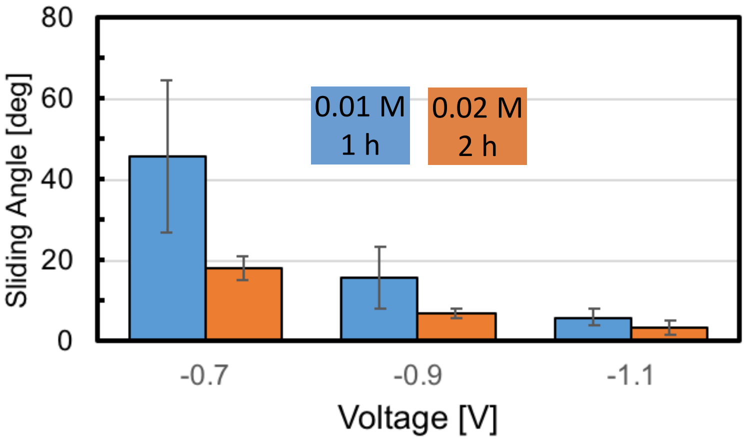
Superhydrophobic Surfaces via electrodeposition





Voltage (V)	0.02M Stearic Acid	STD	0.01M Stearic Acid	STD
-0.5	144.7	9.9	131.5	5.2
-0.7	146.3	2.9	148.4	9.1
-0.9	154.4	3.6	151.2	5.0
-1.1	158.1	3.9	159.6	5.3





Effect of **deposition voltage** and **functionalization**: *Based on the analysis a deposition voltage of –1.1 V and functionalization in 0.02M stearic acid for 2 h was chosen.*

Superhydrophobic Surfaces via Etching

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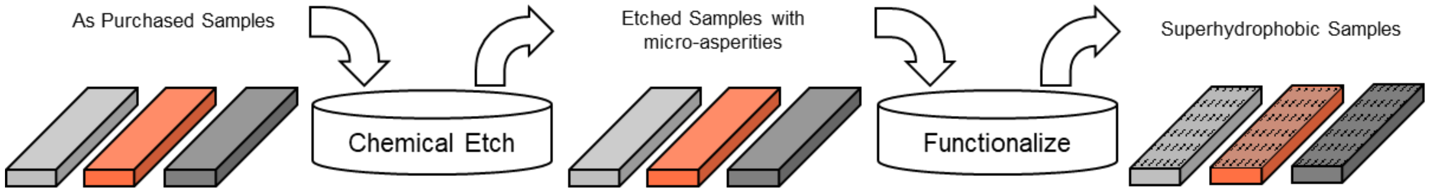
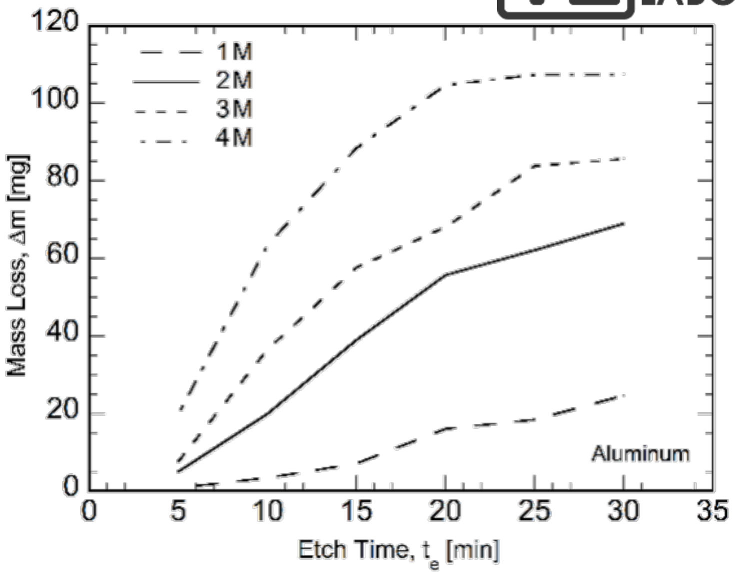
- An alternative method i.e. chemical etching is used to fabricate superhydrophobic copper, aluminum and steel samples.





- The etching process is optimized by highest degree of superhydrophobicity $(\theta_c - 150°)$ with the lowest contact angle deviation (σ_{θ_c}) and mass loss (Δm) from the sample.

$\theta_c\ (\sigma_{\theta_c})$	1M HCL	2M HCL	3M HCL	4M HCL
5 min	110.2° (6.4°)	134.8° (3.4°)	126° (12.6°)	151.8° (1.1°)
10 min	122.3° (8.6°)	149.4° (4.1°)	159.0° (3.5°)	157.8° (4.5°)
15 min	134.9° (4.9°)	159.1° (2.7°)	156.2° (4.4°)	153.6° (3.8°)
20 min	146.7° (1.6°)	160.9° (2.3°)	161.2° (2.1°)	155.1° (1.3°)
25 min	149.7° (3.3°)	159.9° (2.0°)	159.7° (2.6°)	152.0° (4.4°)
30 min	154.7° (4.6°)	157.3° (2.9°)	160.0° (2.0°)	154.2° (2.9°)

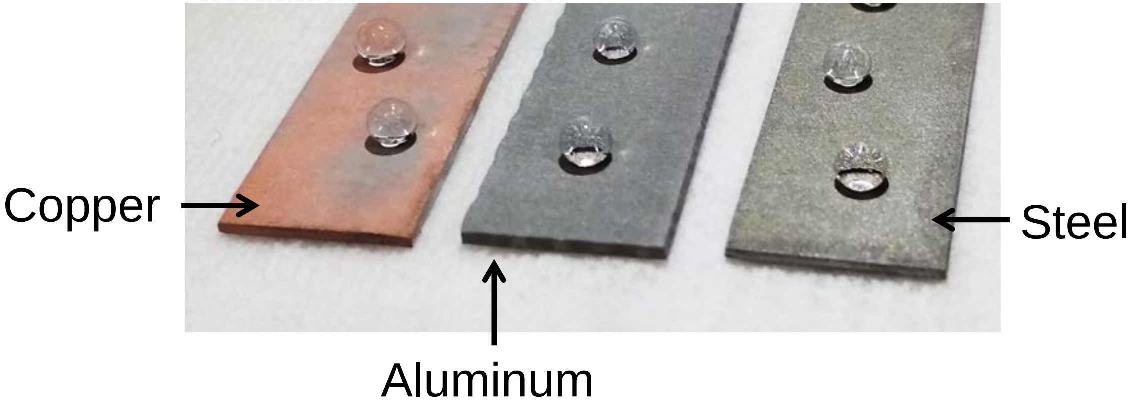
$\frac{(\theta_c - 150°)}{\sigma_{\theta_c} \times \Delta m}$	1M HCl	2M HCl	3M HCl	4M HCl
5 min	-7.822	-0.899	-0.245	0.082
10 min	-0.916	-0.008	0.071	0.027
15 min	-0.439	0.088	0.024	0.011
20 min	-0.128	0.086	0.078	0.036
25 min	-0.006	0.080	0.045	0.004
30 min	0.041	0.036	0.059	0.013

An optimum HCL concentration of 2M and etching time of 15 mins is selected

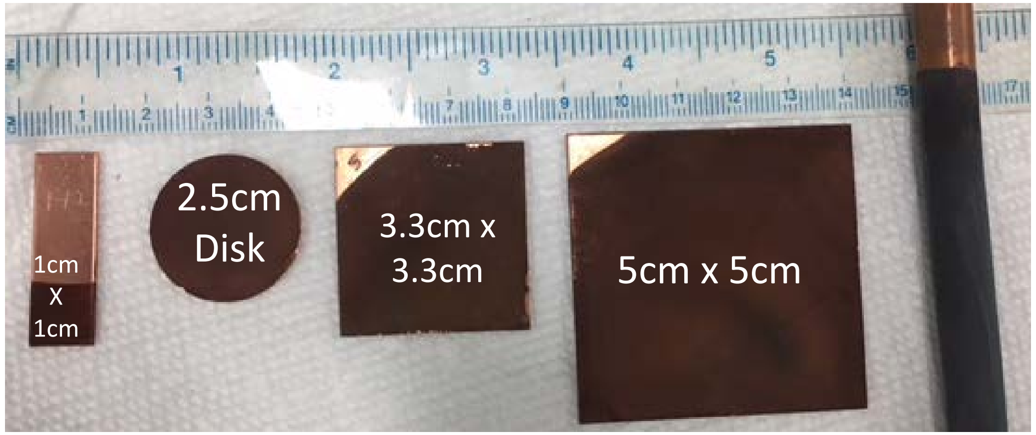
Scalability in Materials, Size, and Shape

We have demonstrated the scalability of the process to a variety of :

1. Materials

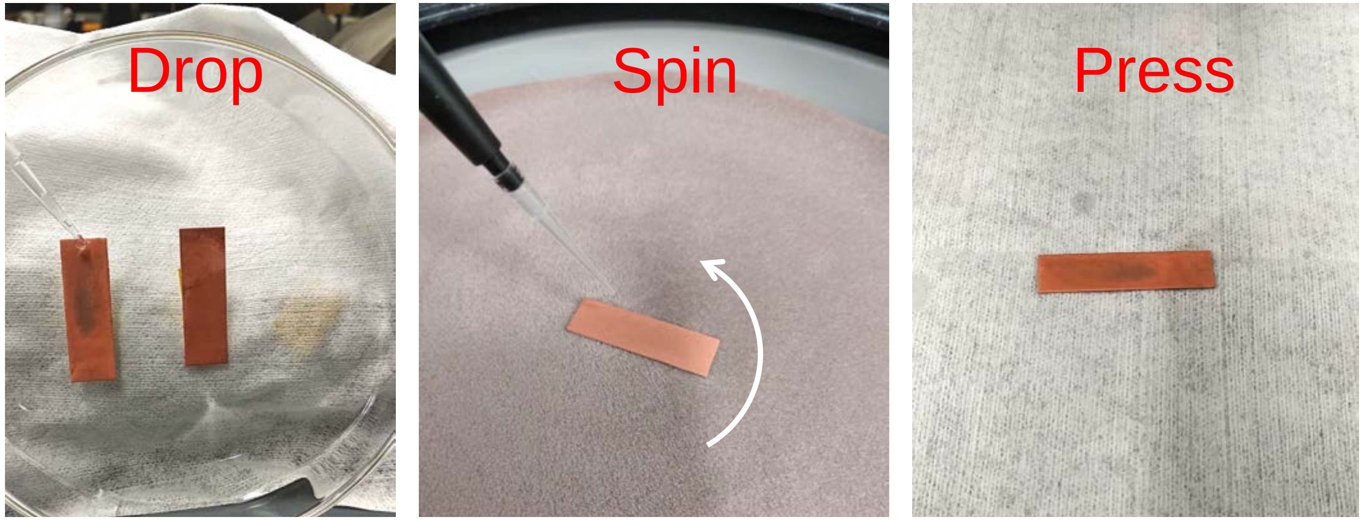


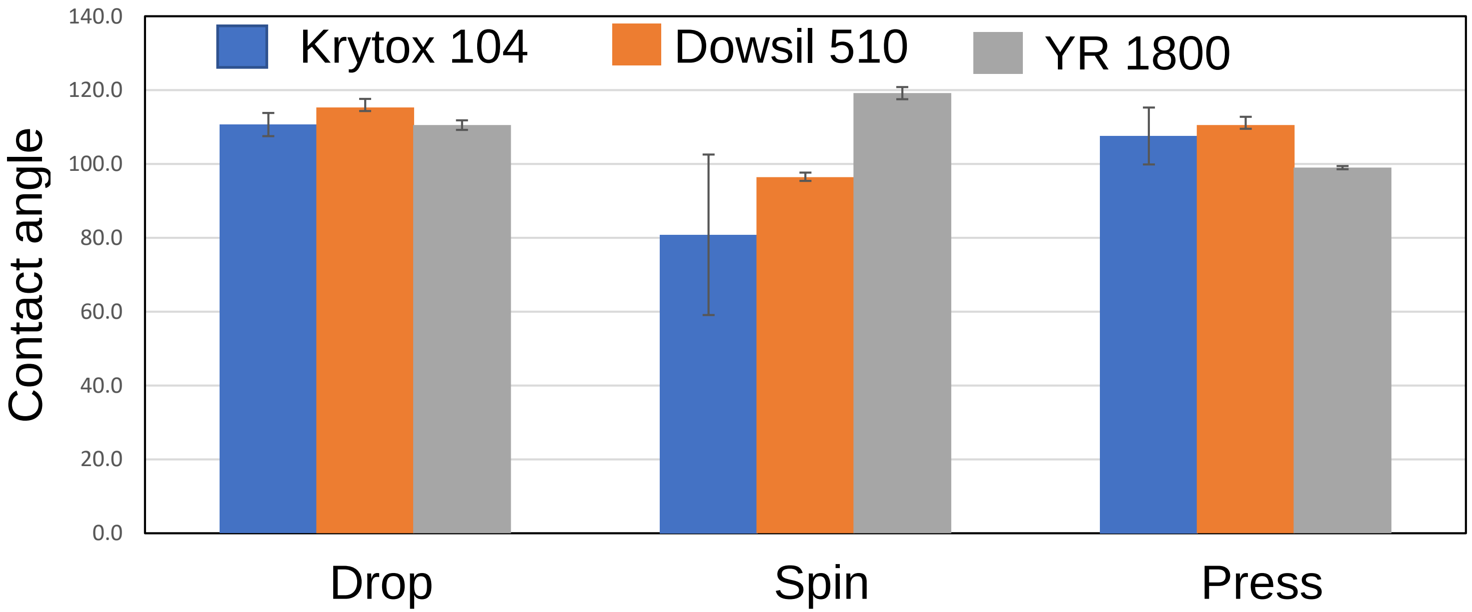
2. Sample sizes



3. Surface shape

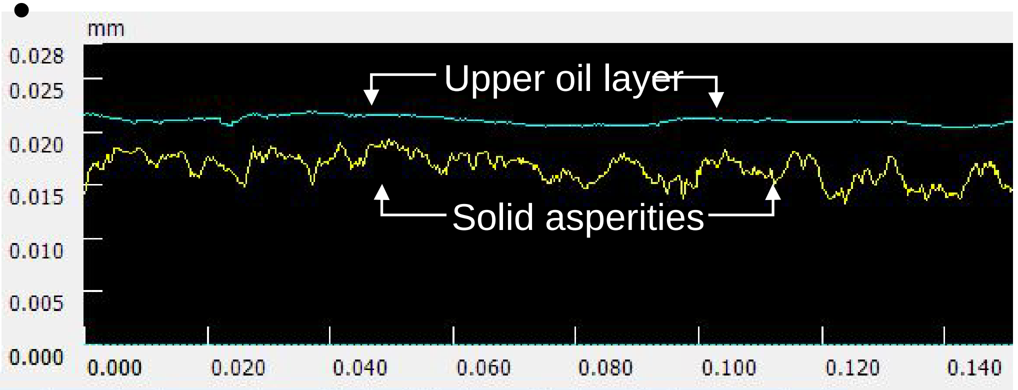
Fabrication of SLIP Surfaces





- All oil infusion method show static contact angle in the range of 100° to 120° within the respective standard deviations.

- Confocal laser microscopic characterization of SLIP surface (Dowsil 510, Press method) shows a uniform film presence of an average thickness of 5-10 µm.

- 

Durability Experiments

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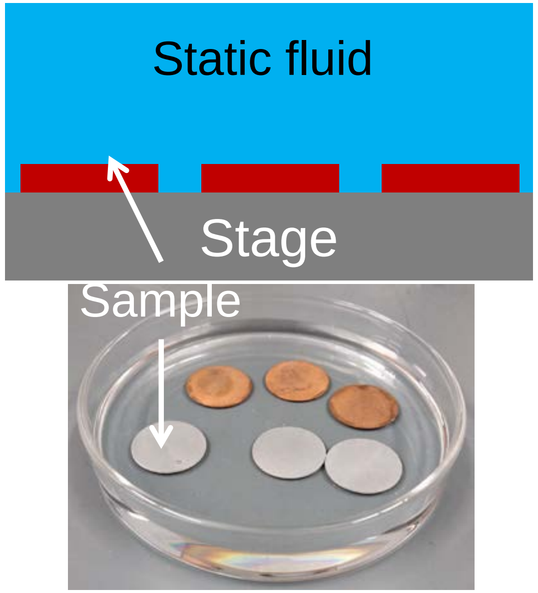
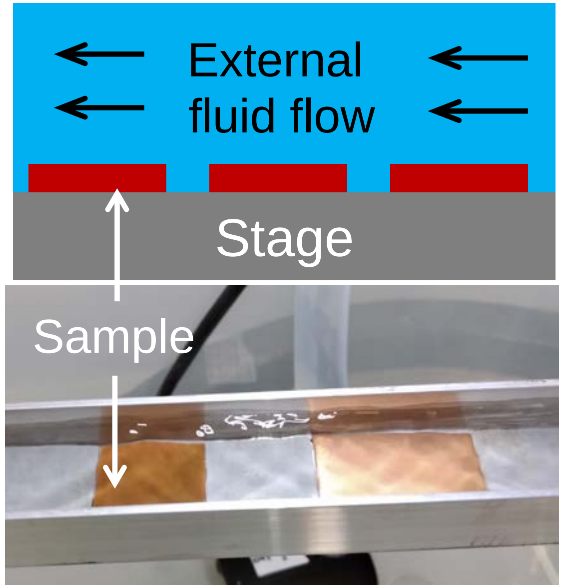
Durability of superhydrophobic and SLIP surfaces of copper and aluminum was tested using different methods. We also studied the effects of functionalizing agents other than stearic acid on the performance of fabricated surfaces.

Static Immersion



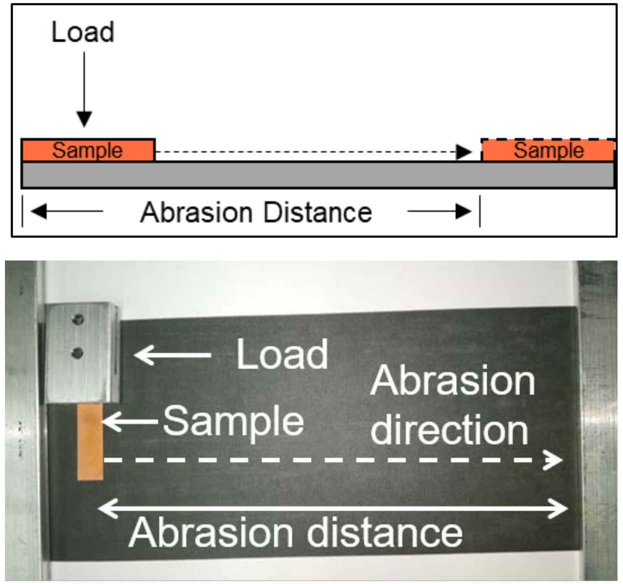
- DI water at temperatures 10°, 22° and 30° C
- 5 % Acetic acid
- 3 % Ammonia

Shear flow



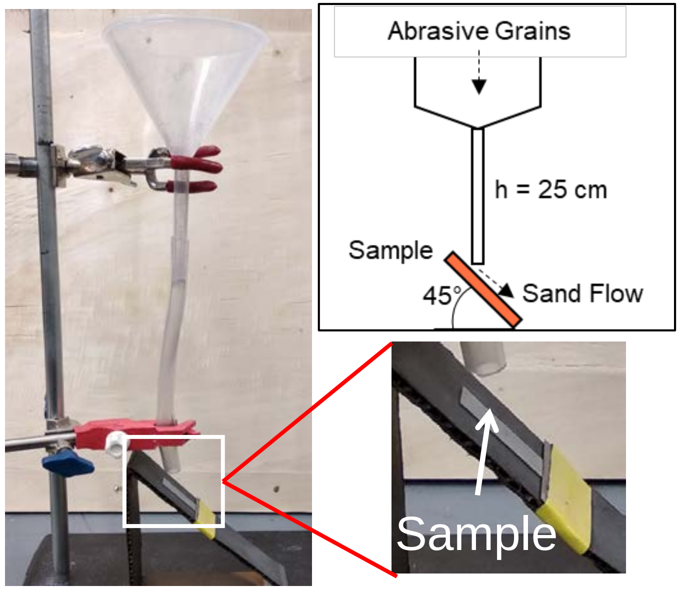
- Average flow velocity: 0.55 m/s
- Flow Reynolds number: $\mathrm{Re} = 2400$

Shear abrasion



- Sandpaper quality: 1000 grits
- Load: 3 Kpa
- Drag speed: 1 cm/s
- Abrasion distance: 20 cm
- ASTM D4060.9768

Falling sand abrasion



- Sand mass: 100 g
- Sand particle size: 100-250 µm
- Falling distance: 25 cm
- Sample inclination: 45°
- ASTM D968.4649

Durability Results for Superhydrophobic Surfaces

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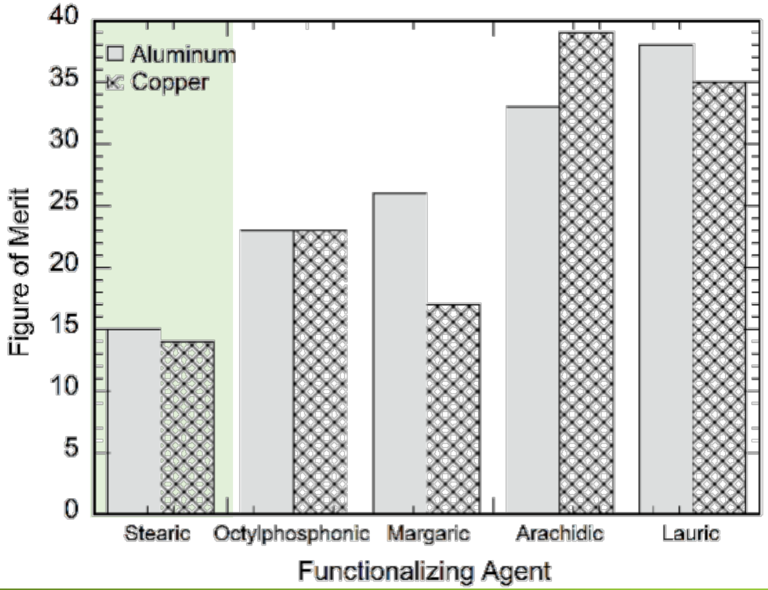
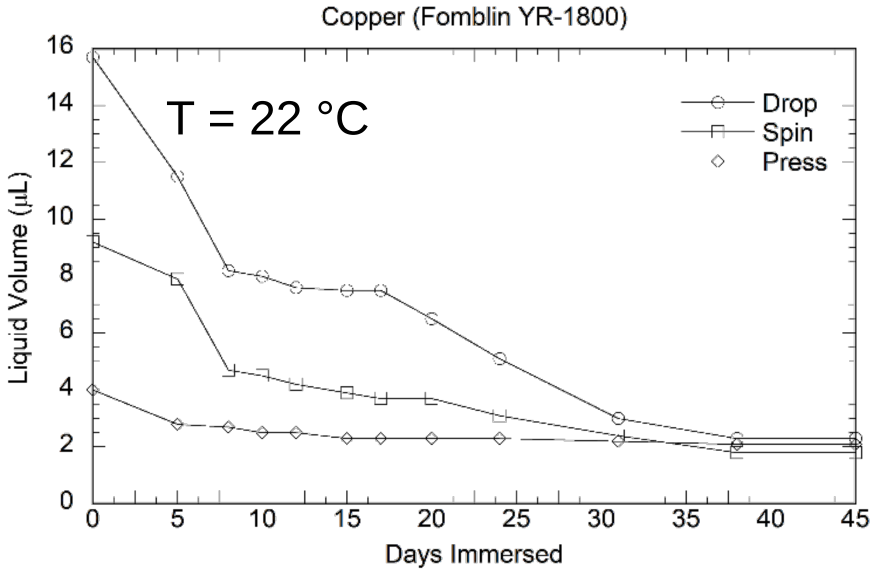
Aluminum	Cost/gram	As Fabricated	10ºC	22ºC	30ºC	5% Acetic Acid	3% Ammonia	Shear Flow	Drag Abrasion	Falling Sand	FOM
Stearic	$0.03 [1]	161.2º [1]	152.6º [1]	148.8º [1]	< 120º	143.7º [2]	151.8º [3]	142.0º [1]	130.9º [1]	137.1º [4]	15
Lauric	$0.32 [2]	156.0º [5]	143.0º [3]	138.6º [5]	< 120º	< 120º [5]	150.1º [5]	< 120º [5]	130.5º [3]	136.2º [5]	38
Margaric	$5.40 [3]	158.6º [3]	150.3º [2]	147.9º [2]	< 120º	133.4º [3]	151.7º [4]	139.3º [2]	122.2º [5]	139.8º [2]	26
Arachidic	$11.10 [4]	157.3º [4]	137.5º [4]	138.7º [4]	< 120º	120.1º [4]	152.2º [2]	131.2º [4]	122.5º [4]	137.7º [3]	33
Octylphosphonic	$33.00 [5]	159.2º [2]	131.3º [5]	144.3º [3]	< 120º	153.1º [1]	155.4º [1]	135.3º [3]	130.6º [2]	142.0º [1]	23

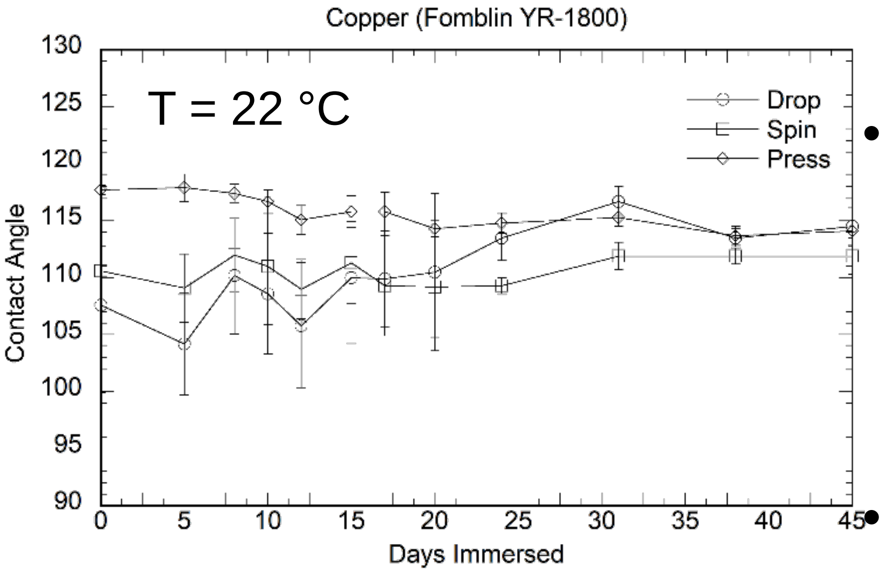


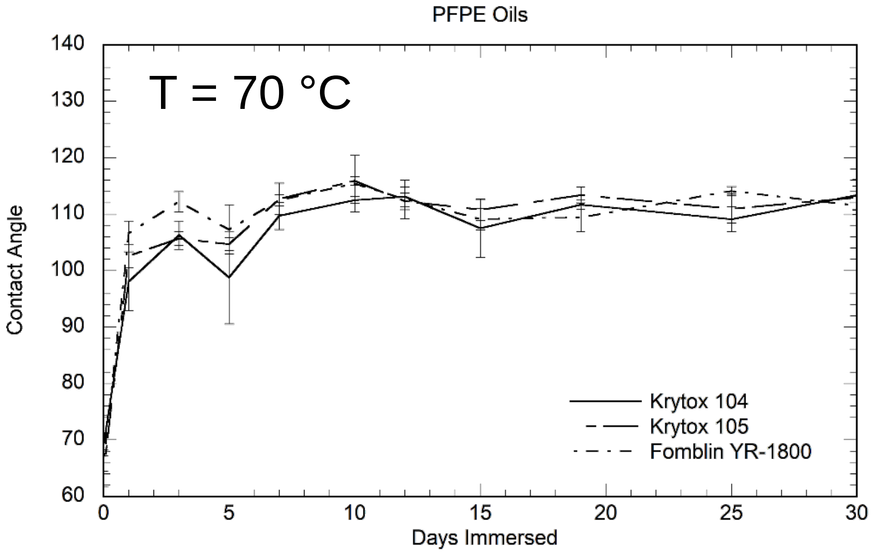
$$FOM = \sum ranks$$

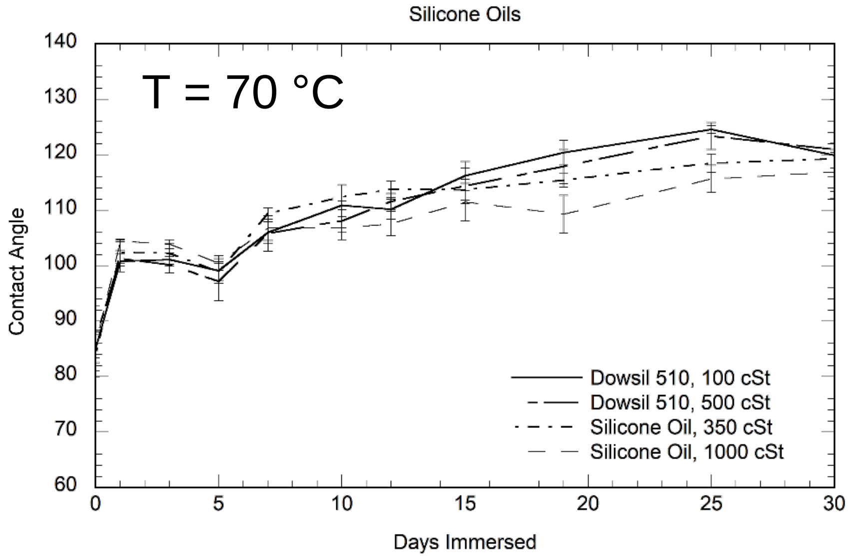
- Smaller figure of merit represents better performance
- Figure of merit analysis indicates that Stearic acid is the optimum functionalizing agent on aluminum and copper based on the durability tests.

Durability Results for SLIP Surfaces: Static Immersion









- Long term behavior: All three oil infusion methods result in identical infusion liquid volume and contact angle measurements at room temperature
- Based on the amount of oil utilized, the ‘press’ method is for oil infusion.
- The results show that the SLIP surfaces are durable to long term water exposure at room temperature and high temperature.

Outline

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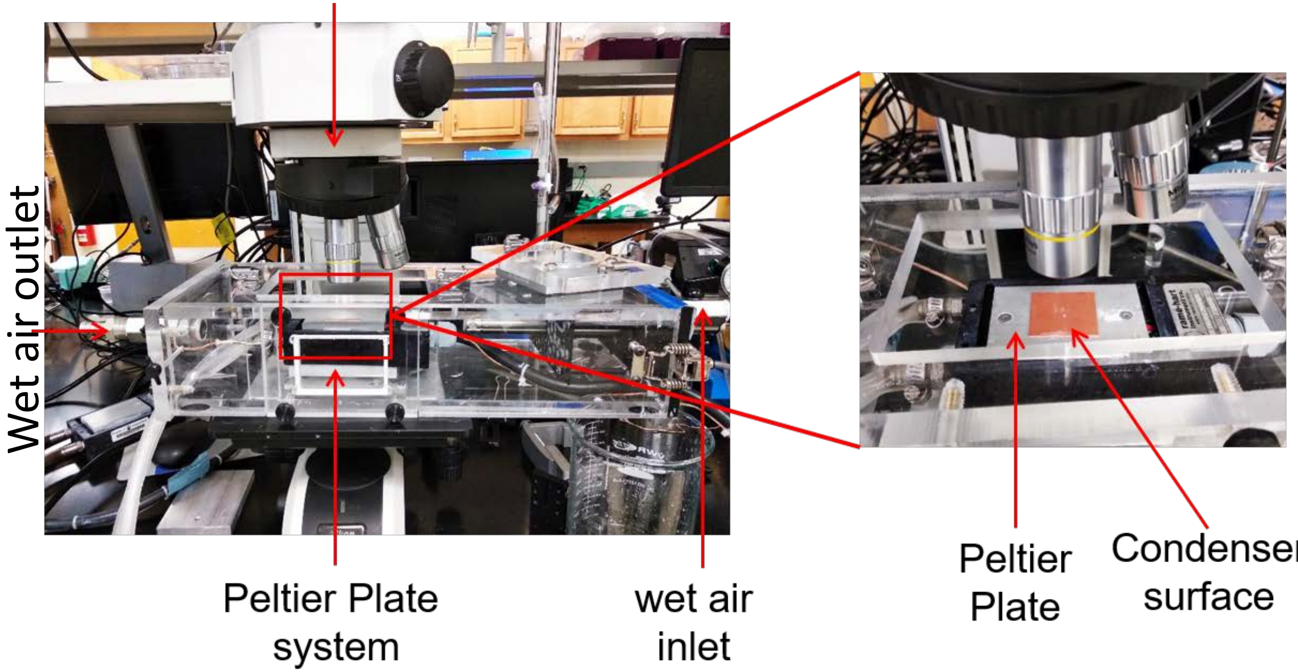
✓ Fabrication and Process Parameter Identification

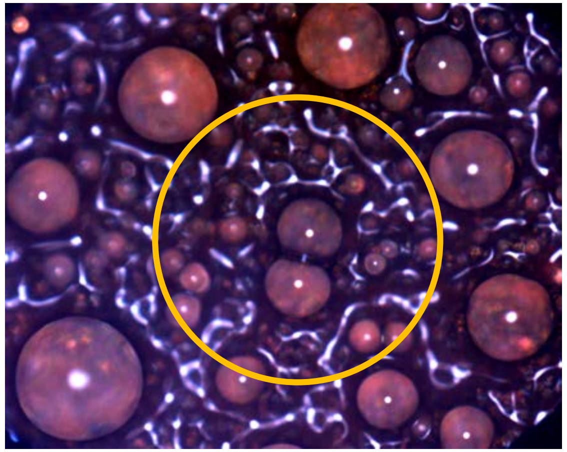
- Condensation Heat Transfer
- Corrosion inhibition on non-wetting surfaces

Condensation Heat Transfer

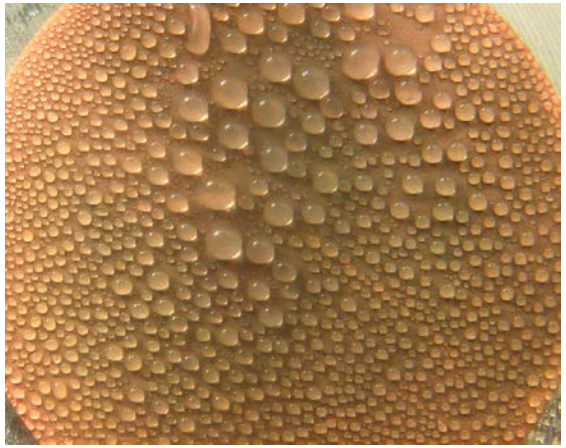
The goal of the condensation heat transfer study is to characterize the nucleation, growth, coalescence and gravity influenced removal of droplets from different surfaces at different operating conditions.



Droplet movement on horizontal surface



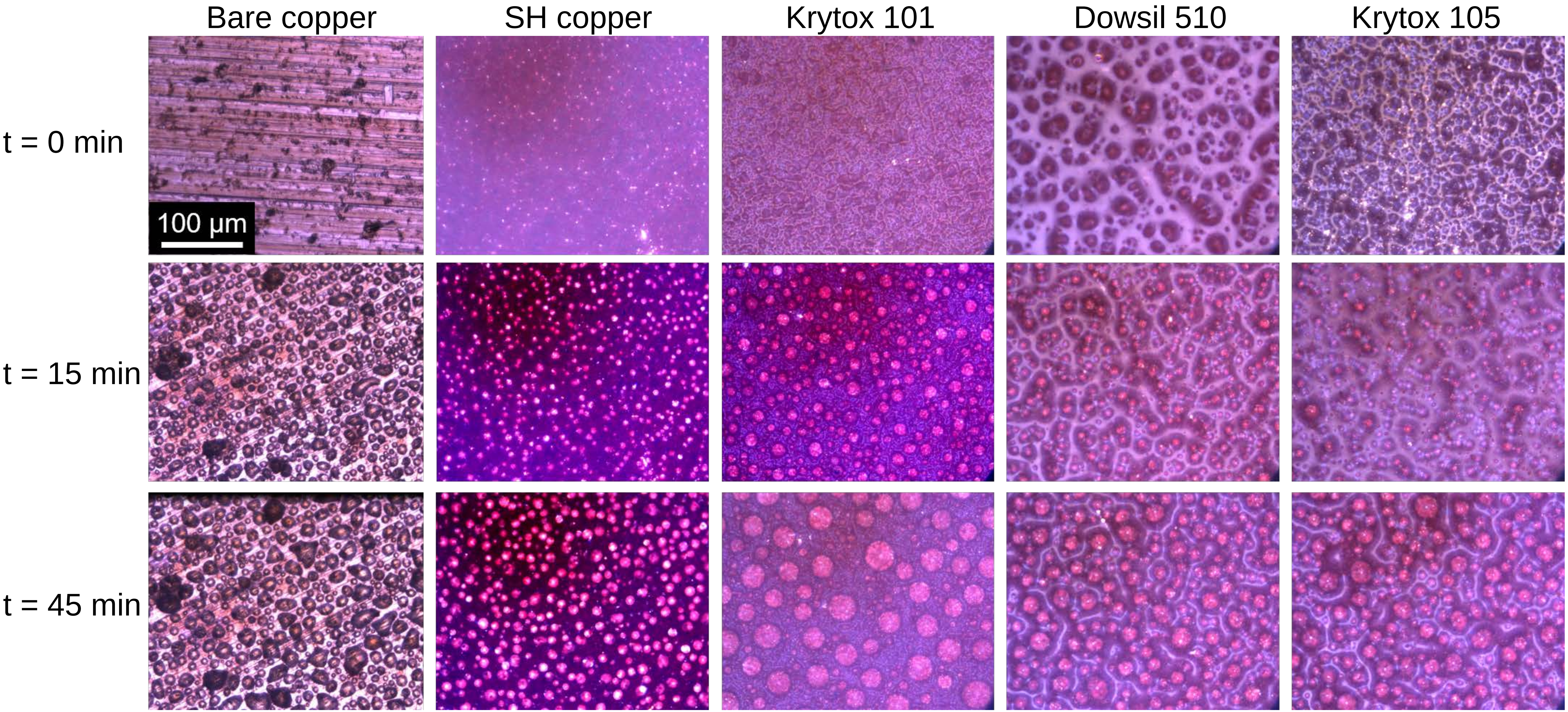
Droplet movement on vertical surface



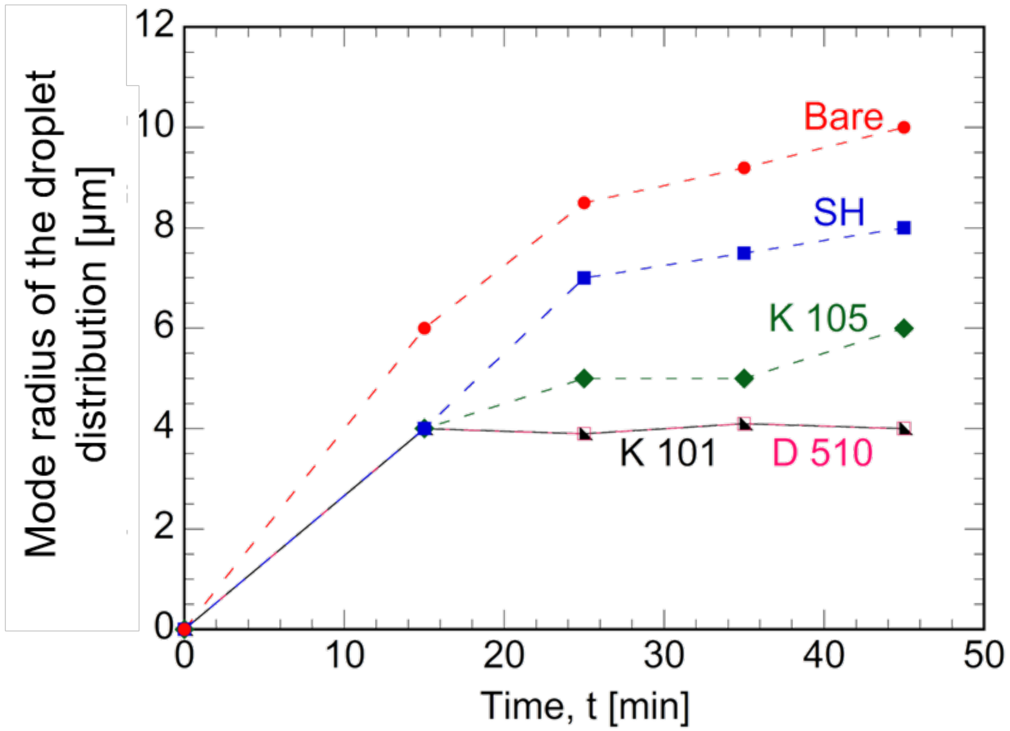
Condensation experimental parameter space

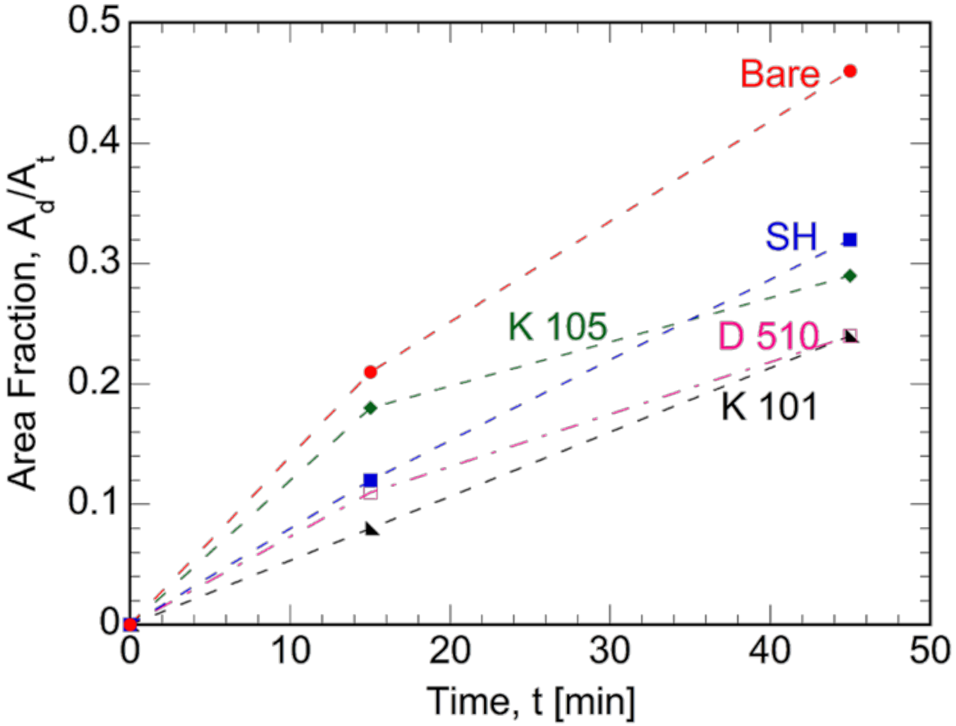
Materials	Copper	Aluminium		
Method of Fabrication	Bare	EDP:V1	EDP: V2	Etching
Infusion Oils	No infusion	Krytox 101	Krytox 105	Dowsil 510
Supersaturation (SS)	1.2	1.8	2.4*	
Surface Orientation	Horizontal	Vertical	Inclined	

Condensate Droplet Growth



Condensate Droplet Size Distribution





- Mode radius values shows that the superhydrophobic surfaces perform better than the bare unstructured surfaces but worse than SLIP surfaces.
- Among the SLIP surfaces Krytox 101 and Dowsil 510 infused samples perform better than Krytox 105.
- Area fraction of the surface covered by the condensate droplets show the potential of further nucleation of condensate droplets.

Outline

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- ✓ Fabrication and Process Parameter Identification
- ✓ Condensation Heat Transfer
- Corrosion inhibition on non-wetting surfaces

Corrosion Inhibition on Non-wetting Surfaces

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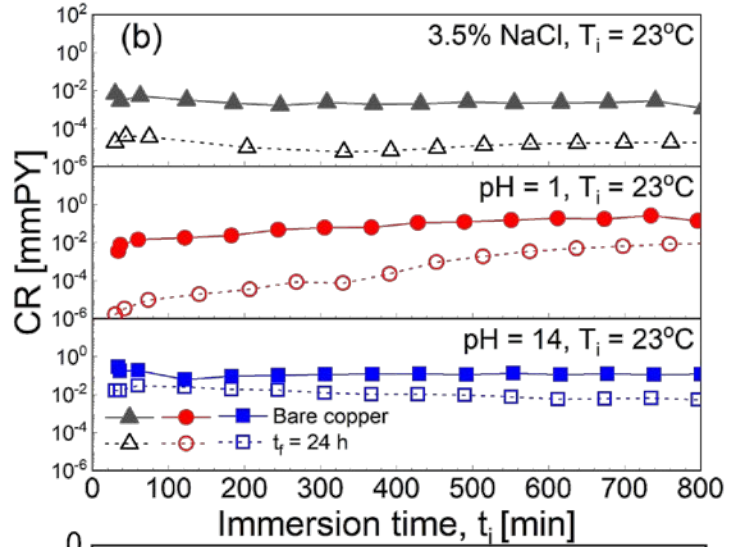

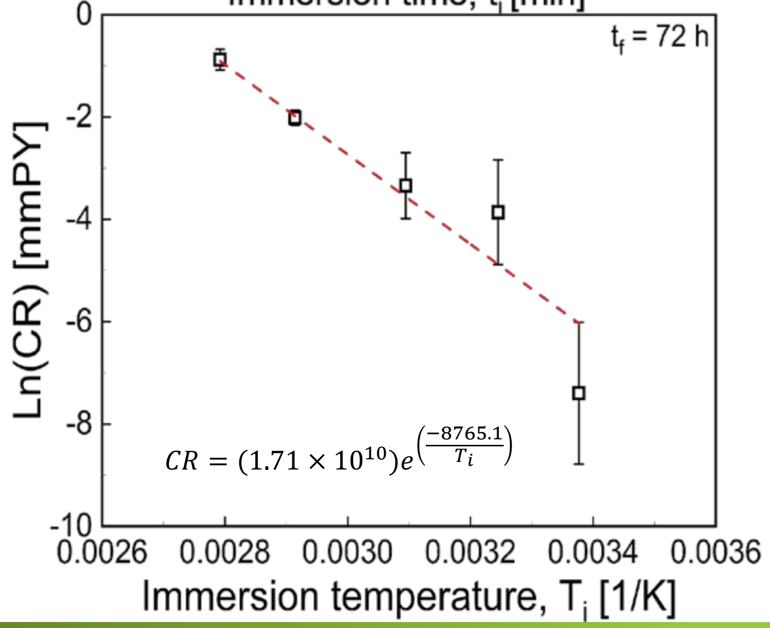

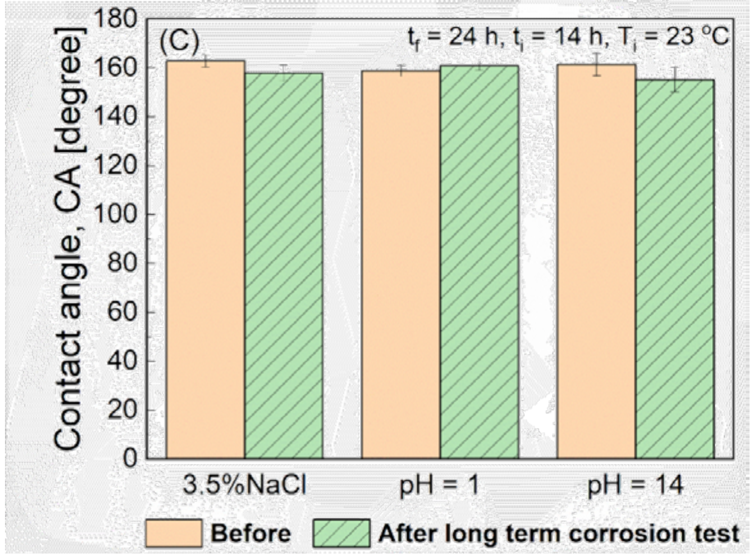

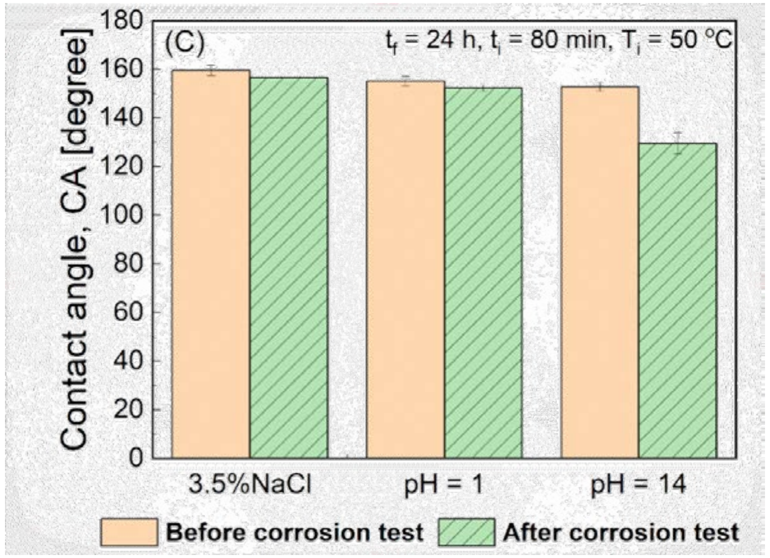

- Linear polarization immersion tests at three different pH levels show significantly lower corrosion rate for superhydrophobic surfaces at room temperature and elevated temperature.
- Long term stability tests show no effects on the wettability of the samples at both room temperature and elevated temperature of 50° C.
- Corrosion rate is correlated to immersion temperature using Arrhenius plot.

Corrosion Inhibition on Non-wetting Surfaces

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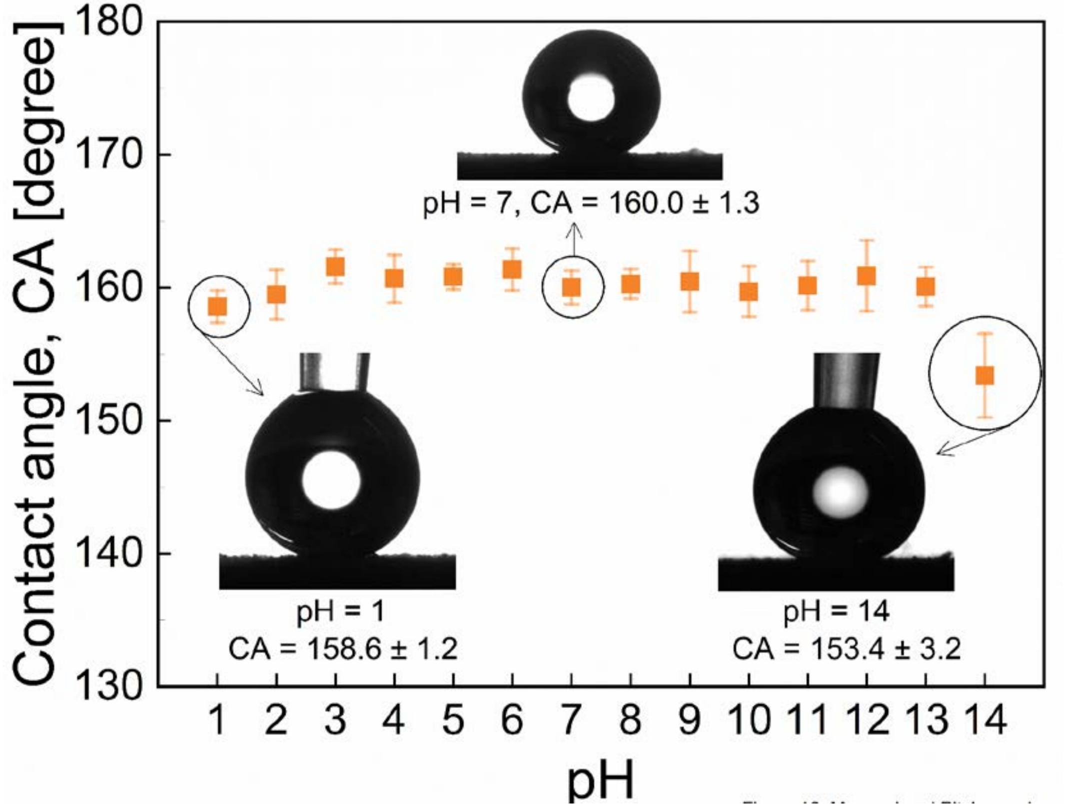
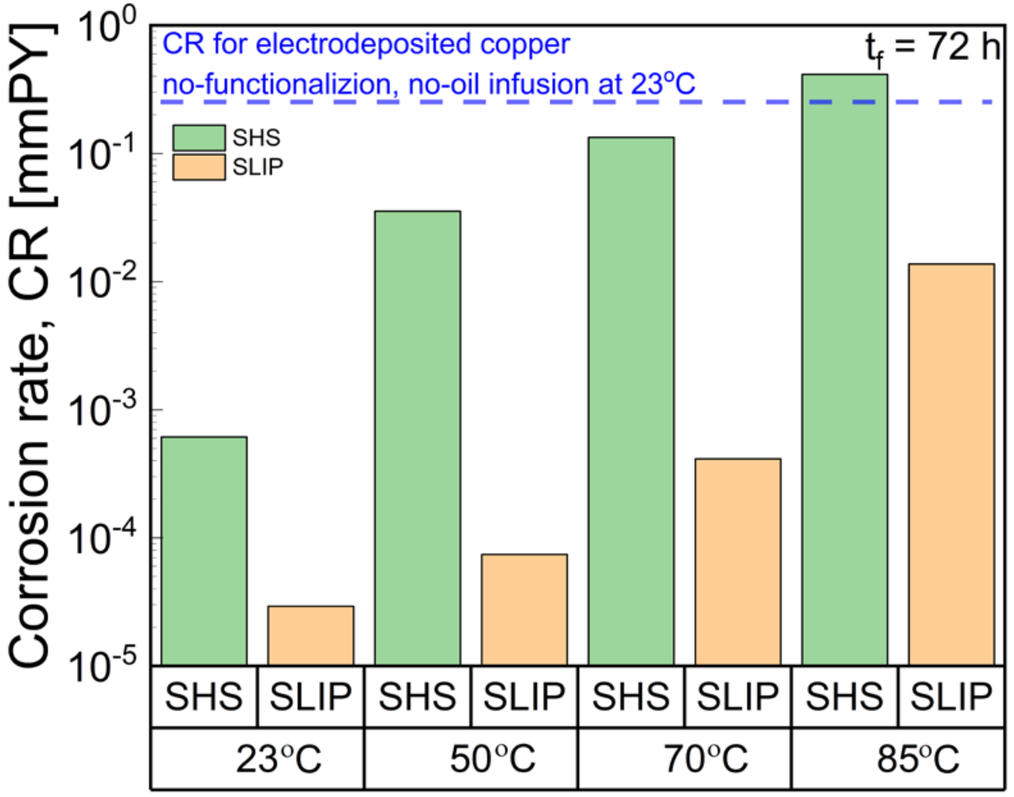
The corrosion inhibition is again correlated to apparent static contact angle to understand the effects on surface energy modifications for a wide range of pH levels.



Experiments on SLIP surface (infused with Dowsil 510) point to the corrosion inhibition for a range of temperature values.



Concluding Remarks

- Process parameters for the fabrication of superhydrophobic and SLIP surfaces are determined through different durability tests. The fabrication process of superhydrophobic surfaces is scaled to a variety of materials, shapes and sizes.

- Experimental data from the durability experiments promise sustained non-wetting characteristics of the superhydrophobic and SLIPS surfaces.

- Linear polarization experiments for a wide range of pH values (1 to 14) at room temperature and elevated temperatures show significant reduction in the corrosion rate of electrodeposited superhydrophobic and SLIP surfaces.

- Experiments on the condensation heat transfer on horizontal surfaces point to enhanced condensation on SLIP surfaces fabricated using ‘press’ method as compared to conventional unstructured surfaces.

Publications so far

1. Analytical model for laminar drag reduction on liquid-infused structured non-wetting surfaces. *Applied Materials and Interfaces* (in review).

2. Fractal model for laminar drag reduction on multiscale liquid-infused rough surfaces. *Langmuir* (in review).

3. Durability of superhydrophobic aluminum and copper surfaces fabricated via etching. *Langmuir* (in review)

4. Corrosion of superhydrophobic copper surfaces fabricated via electrodeposition. *Applied Materials and Interfaces* (in review)

5. Fabrication of superhydrophobic engineered materials by etching. *Langmuir* (in review).

Thank you !

Thermal resistances in condenser design: