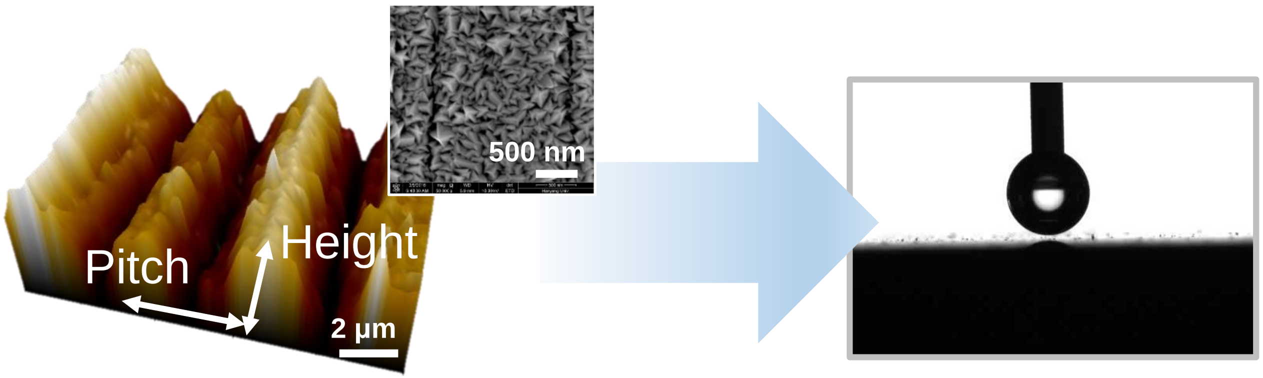
Capillary wicking effect of a Cr-sputtered superhydrophilic surface for enhancement of pool boiling critical heat flux



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2016 Autumn KNS, Room: 103, OCT 28, 2016.

Contents

Background

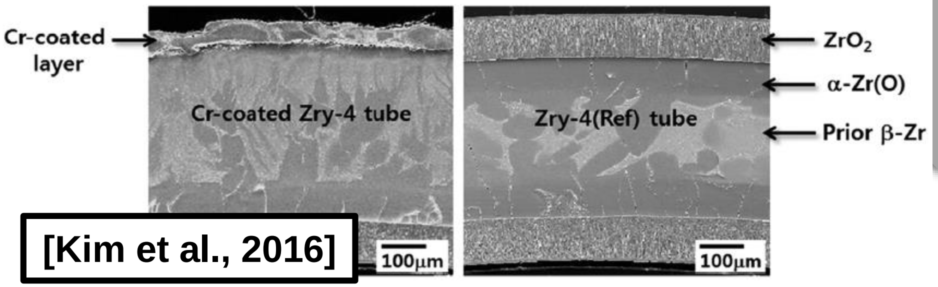
After the Fukushima accident,
Advanced ATF (Accident-Tolerant Fuel) design

Major issues
- Improved Reaction Kinetics with Steam
- Slower Hydrogen Generation Rate
- Improved Fuel Properties
- Improved Cladding Properties
- Enhanced Retention of Fission Products

Aimed components
- Advanced fuel
- Advanced fuel cladding
  - ✓ Reduced steam reaction
  - ✓ Reduced hydrogen generation
  - ✓ Improved aging-resistance

Being considered
- Iron-based alloys
- Surface coating on Zr-based alloys
  - ✓ Manufacturing process of Zr-based alloys
  - ✓ High melting temperature
  - ✓ High neutron economy

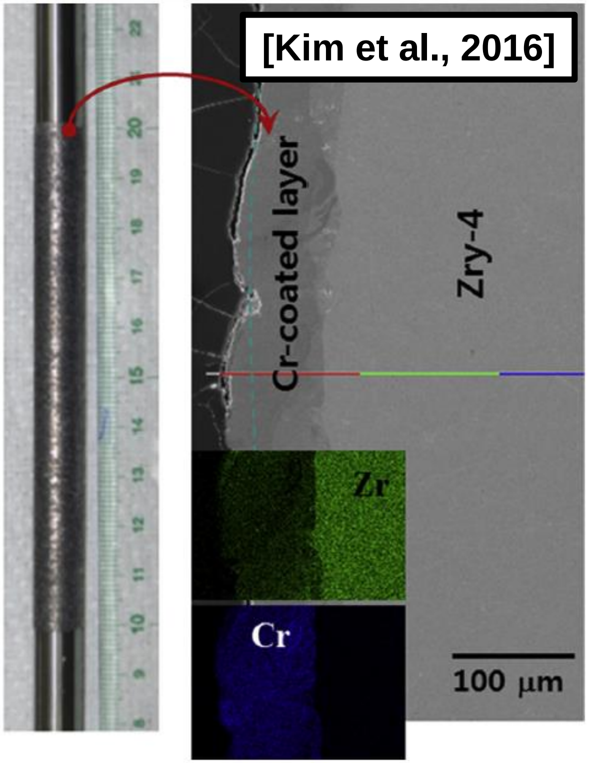
Aging-resistant surface coating



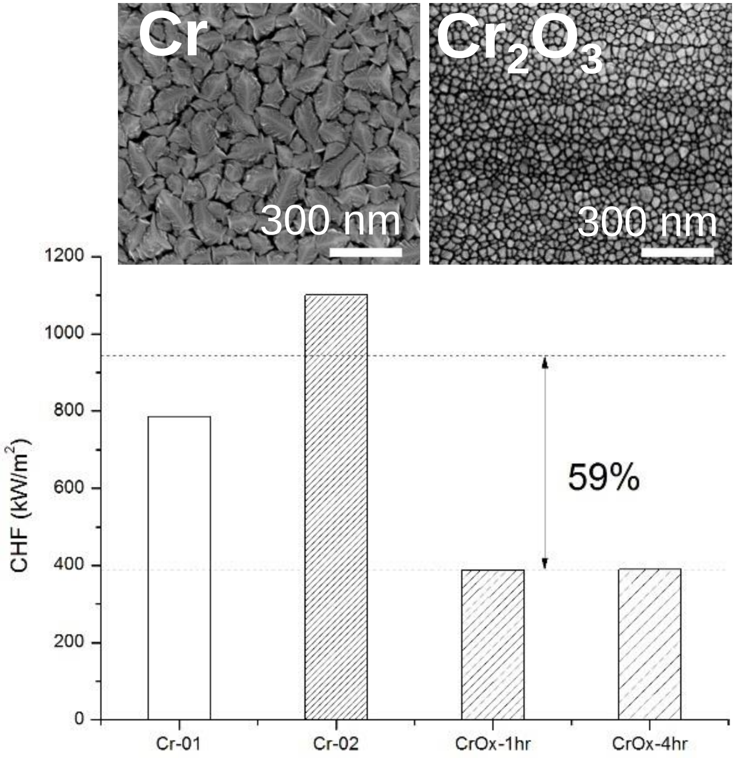
[Kim et al., 2016]

Background

Material aspect
Layer characteristic
Thick and dense



Boiling aspect
Surface characteristic
Micro/nanostructure

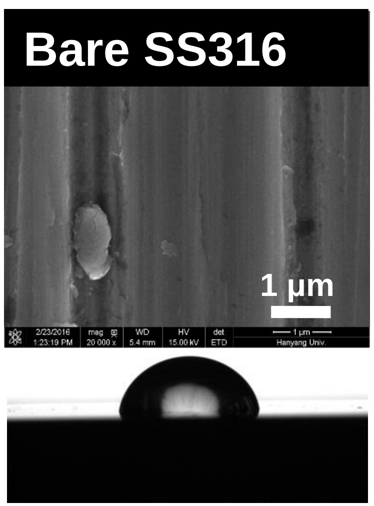


How to produce aging-resistant (FeCrAl, Cr, SiC…) thin-film layered surfaces favorable to BHT?

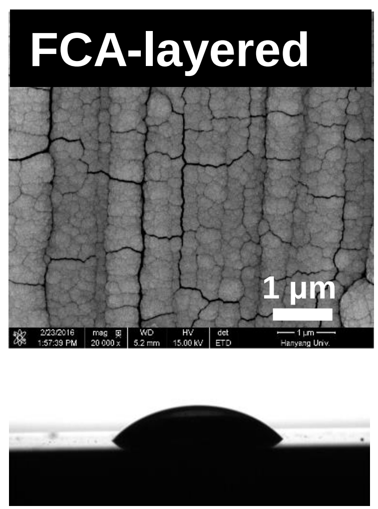
Background

- **Previous studies (CrN, Pure Cr, SiC…)**
  - ✓ Uniform and smooth particle distribution
  - ✓ No concerns for roughness
  - → reduced nucleation and wetting performance
  - → decrease in CHF
- **Present study (FeCrAl, Pure Cr)**
  - ✓ Uniform but **rough** particle distribution
  - ✓ Superhydrophilic property
  - → enhanced wetting performance
  - → increase in CHF

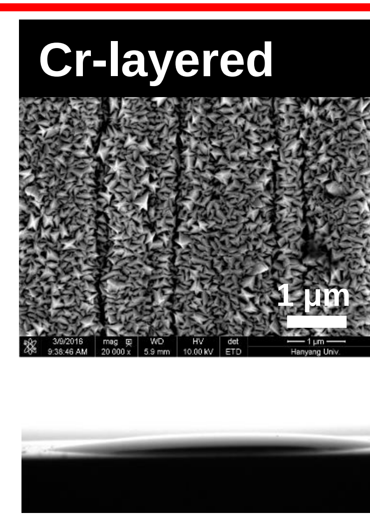
Roughness control



Hydrophilic



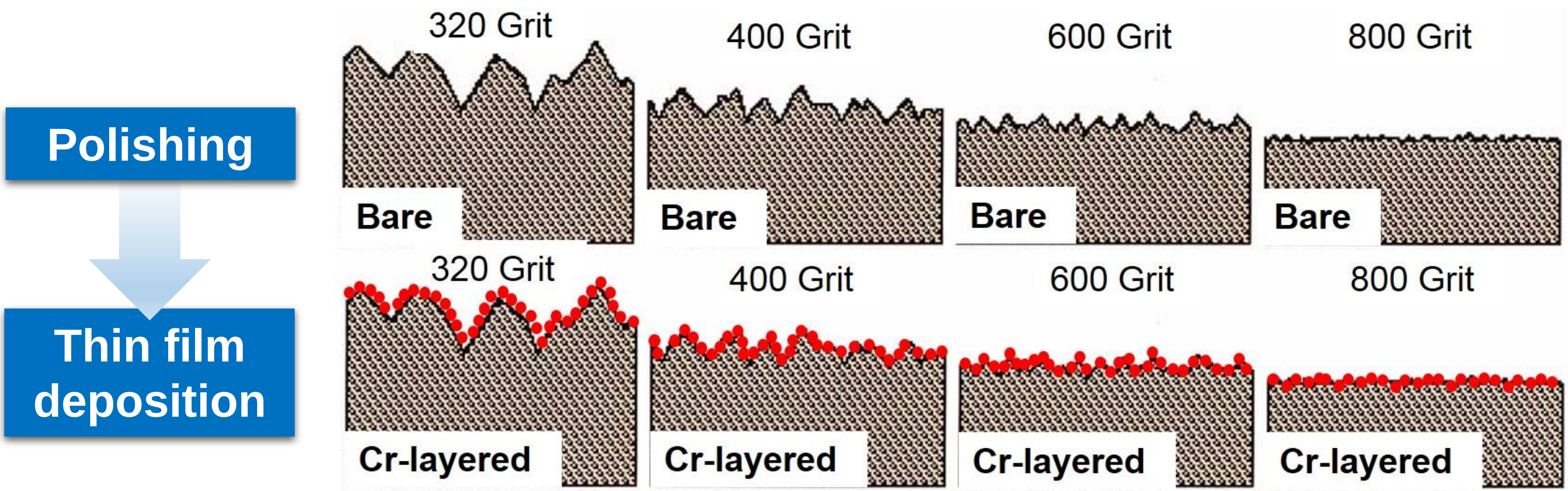
Hydrophilic



Superhydrophilic

Objective

- **Objective**
  - ✓ To investigate roughness effect of Cr-layered superhydrophilic surfaces on capillary wicking and pool boiling CHF

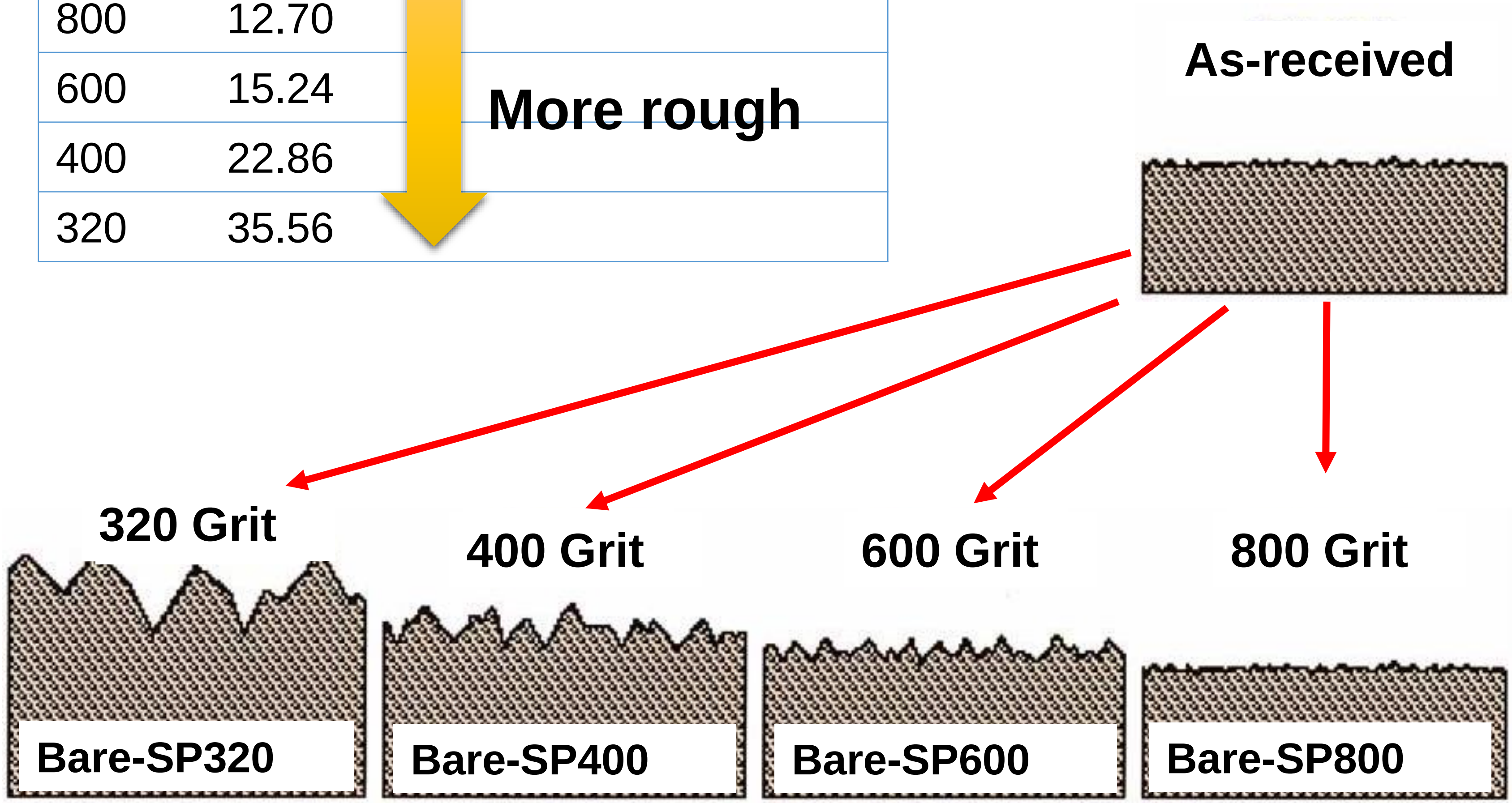


Surface preparation

Surface polishing

Grit	Average particle diameter (μm)
800	12.70
600	15.24
400	22.86
320	35.56

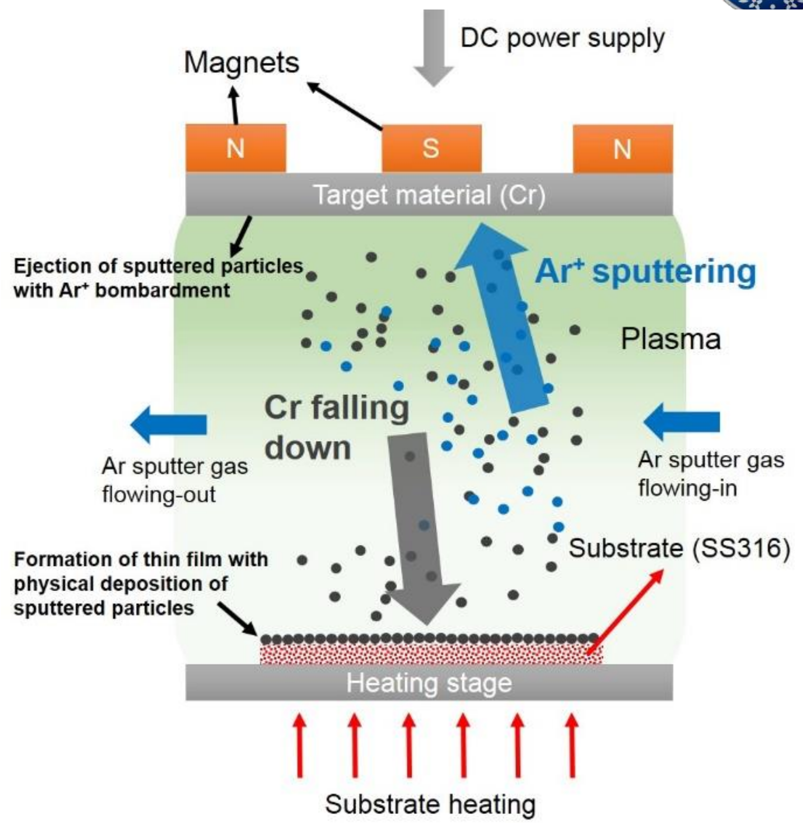
More rough

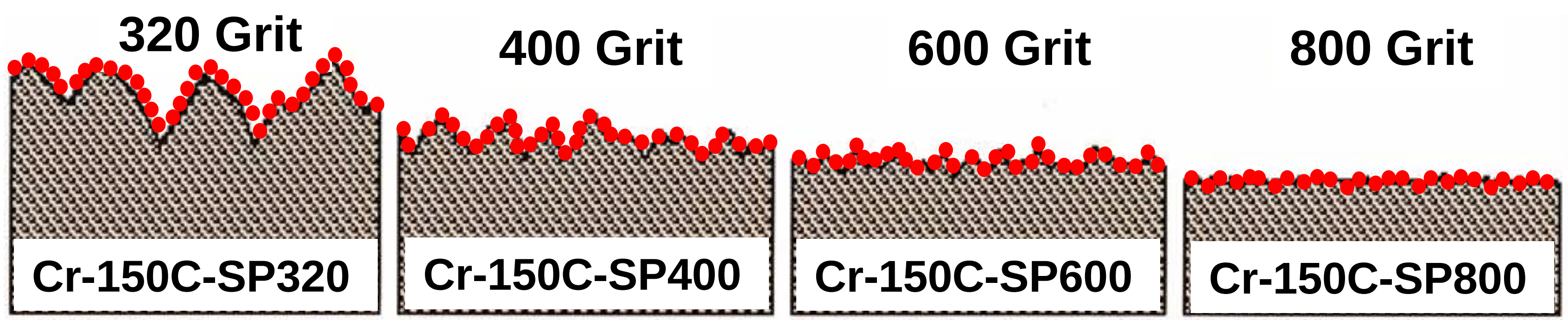


Surface preparation

DC magnetron sputtering

Sputtering condition	
Substrate material	SS316 plate
Target material	Pure Chromium (Cr, 99.95%)
Substrate temperature (°C)	150
Exposure time (hour)	1
Base pressure (Torr)	1×10^{-5}
Working pressure (Torr)	1×10^{-2}
DC power (W)	150 ~ 160
Argon flow rate (sccm)	29.7

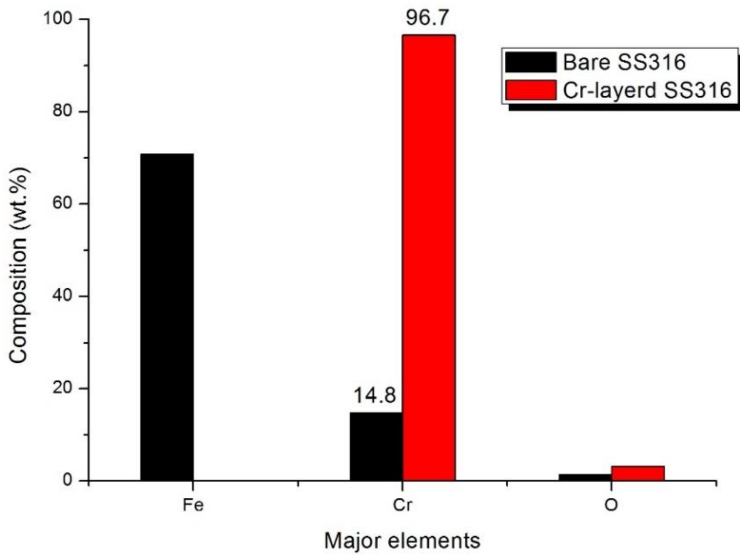




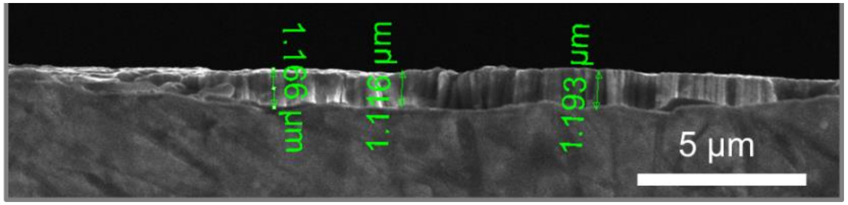
Surface characteristics

Thin film growth

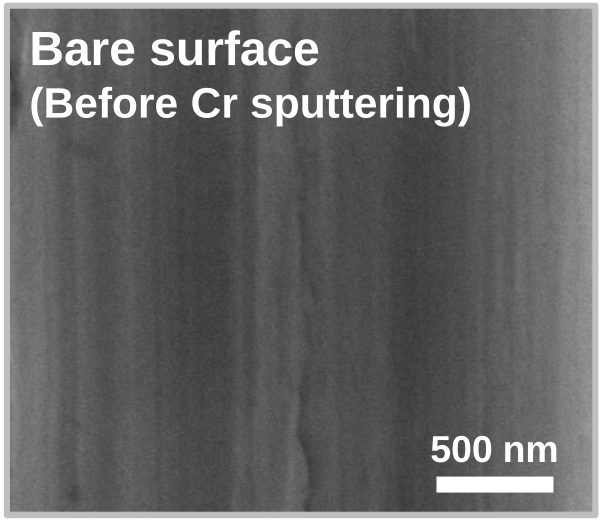
- **Cr composition: 96.7 wt.%**

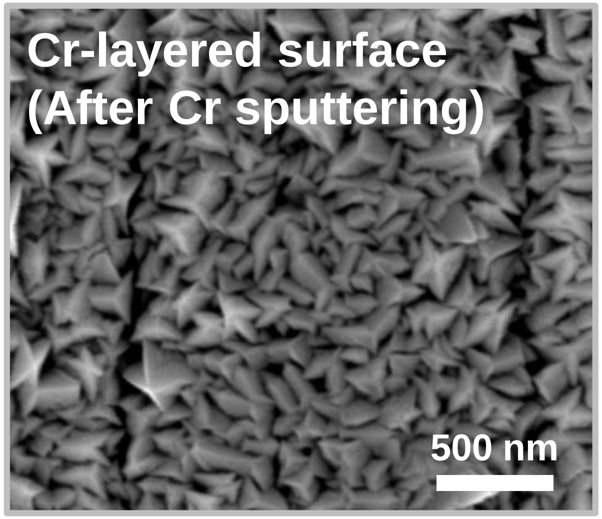


- **Thickness of thin film: > 1 μm**



- **Cr particle size: ~ 200 nm**

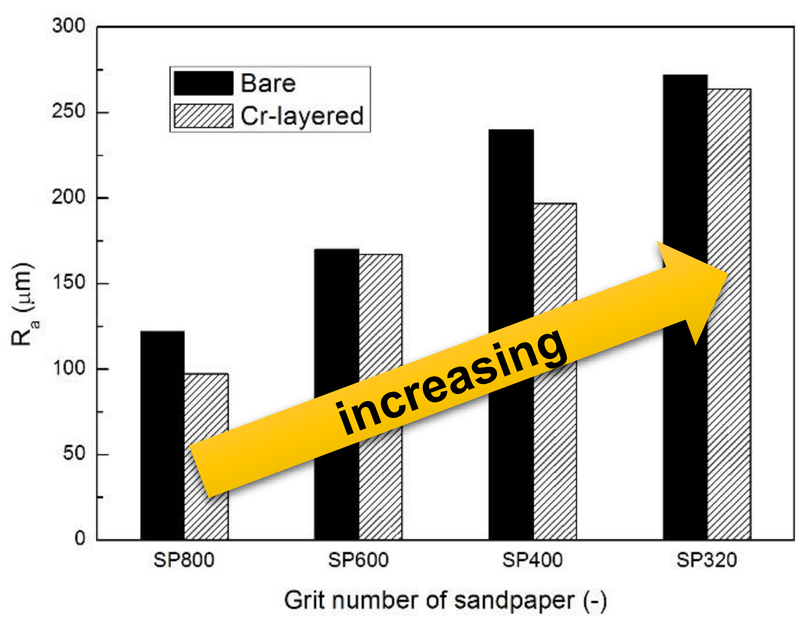


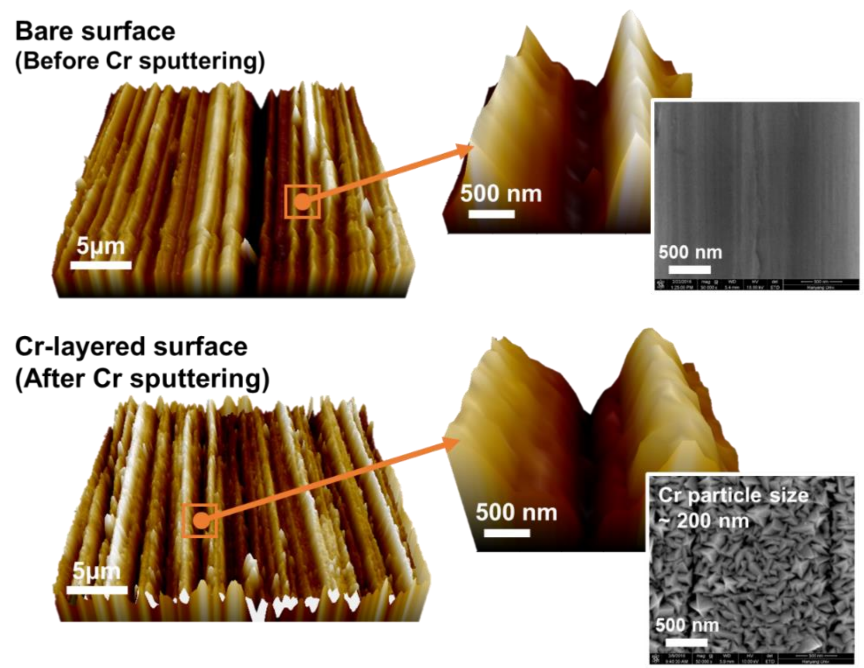


Surface characteristics

Surface roughness

Test specimen	Grit number of sandpaper	Number of measured point (-)	R_a (nm)	R_{sm} (μm)	r (-)
Cr-SP800	800	3	101±4	1.88±0.09	1.09±0.02
Cr-SP600	600	3	183±40	2.46±0.43	1.17±0.05
Cr-SP400	400	3	213±42	2.86±0.36	1.15±0.02
Cr-SP320	320	3	258±45	3.18±0.50	1.20±0.002





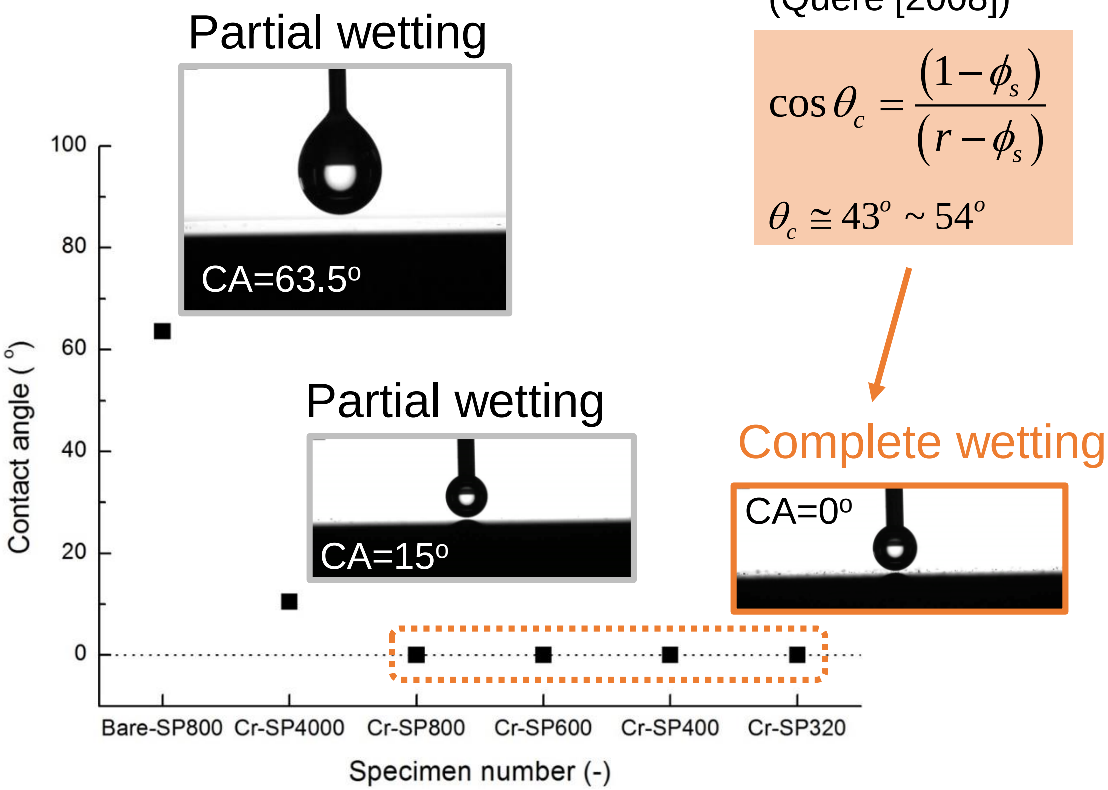
Surface characteristics

Surface wettability

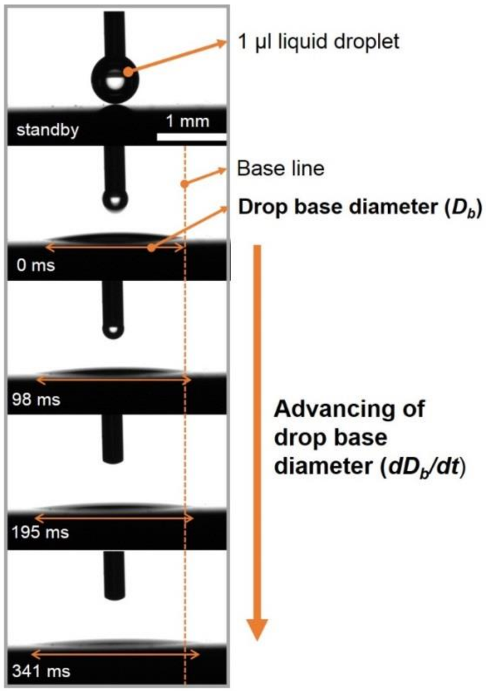
Wicking criterion
(Quéré [2008])

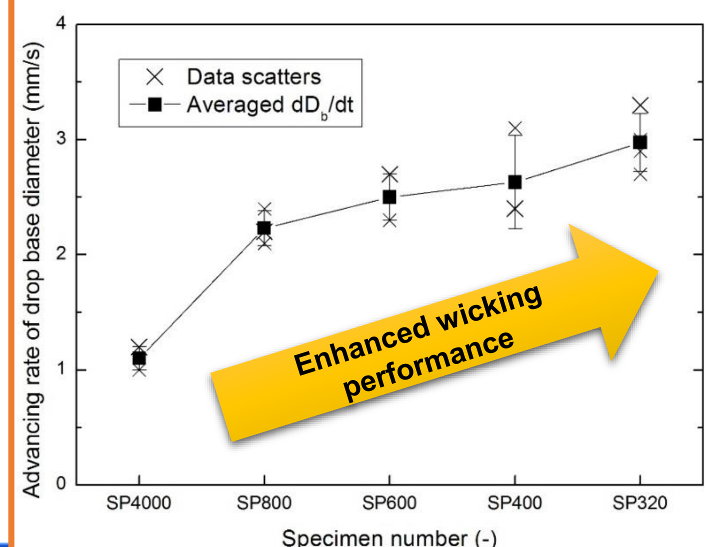
$$\cos\theta_c = \frac{(1-\phi_s)}{(r-\phi_s)}$$

$$\theta_c \cong 43^o \sim 54^o$$



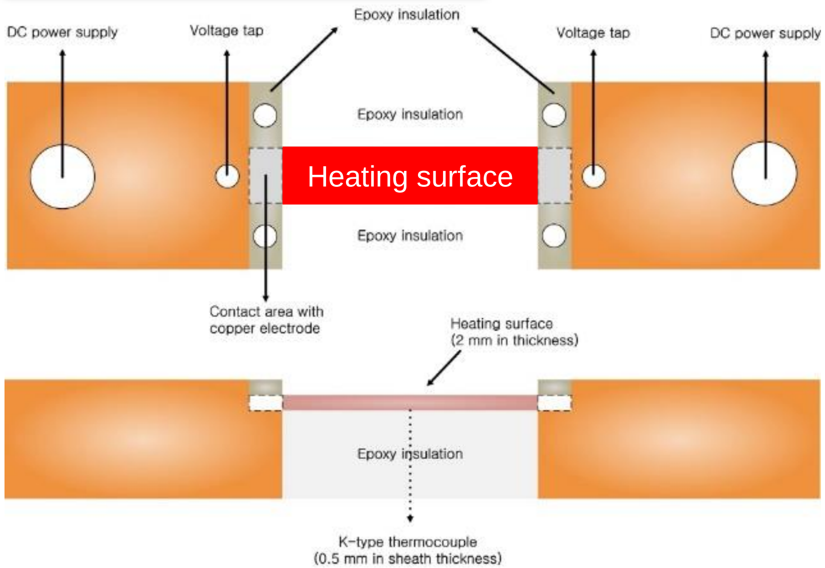
Dynamic wetting



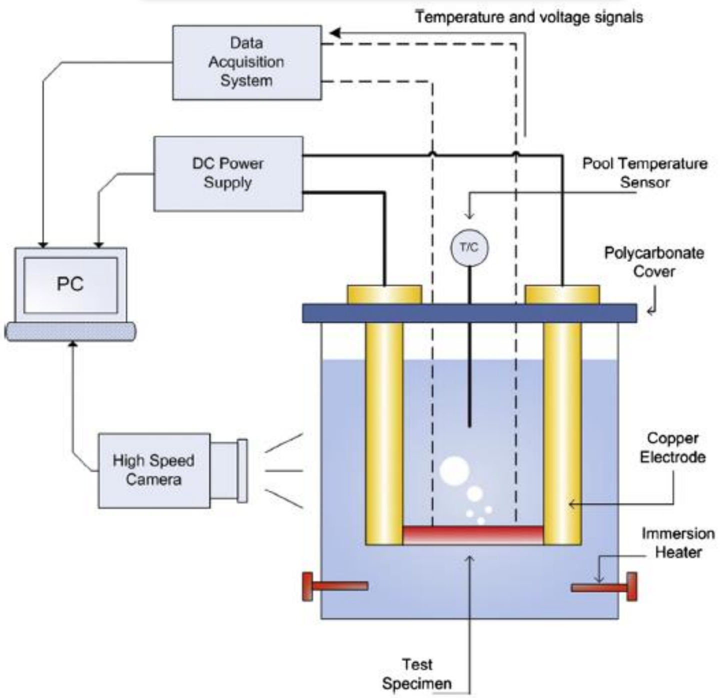


Experimental description

Test section



Pool boiling facility



Test matrix

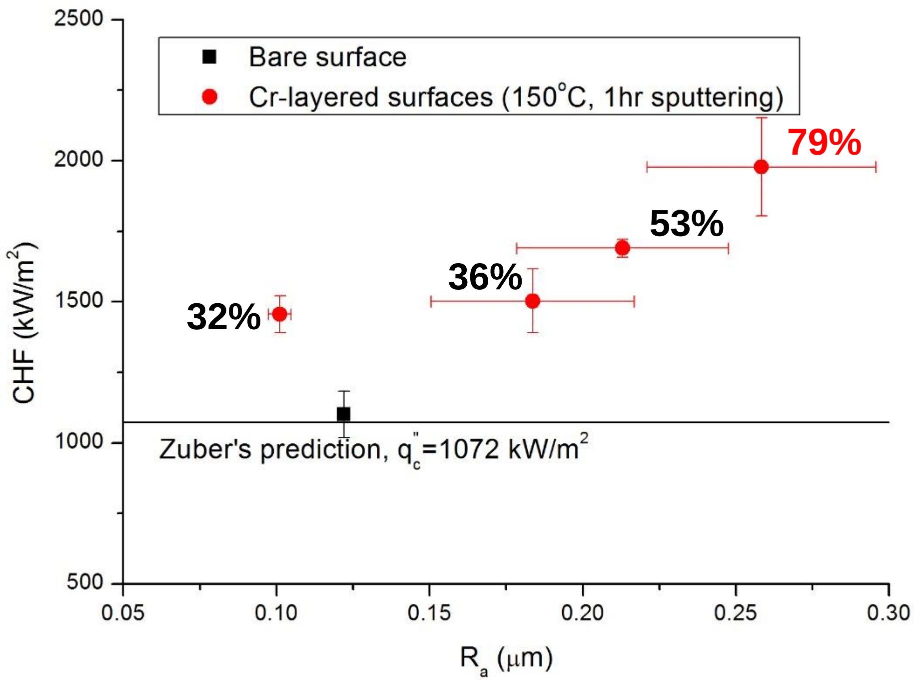
Test specimen	**Cr-layered SS316, bare SS316**
Shape and size	Flat-plate, 25X10X2 mm^3
Grit number of sandpaper (controls base roughness)	**320, 400, 600, 800**
Heating method	DC joule heating
Test condition	Saturated at atmospheric pressure
Working fluid	DI water (~10 MΩ-cm)
Heater orientation	Upward-facing (horizontal)

Results and discussion

- **CHF comparison between Cr- and FeCrAl-layered surfaces**

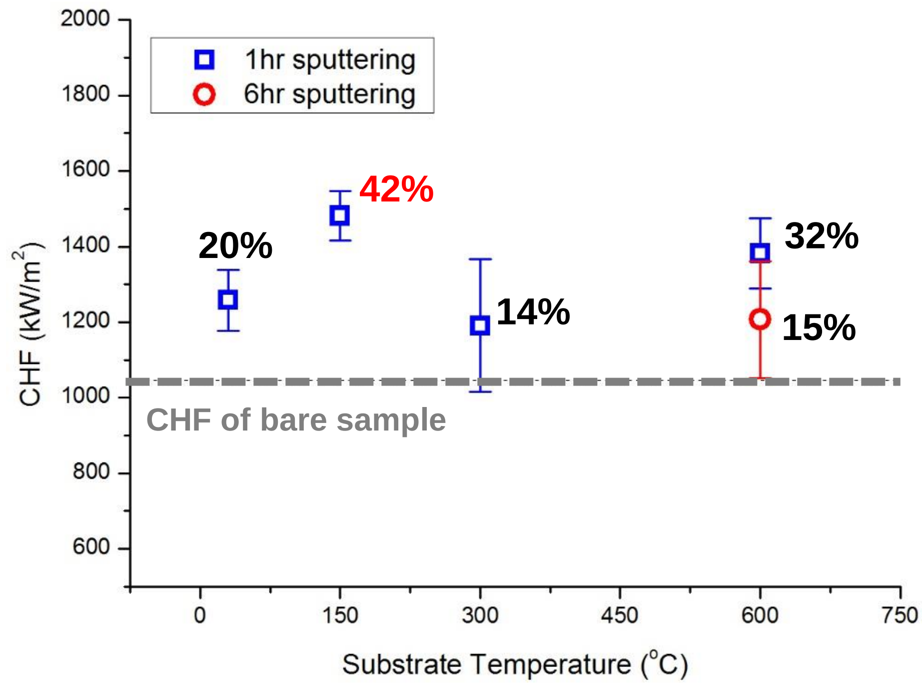
Cr sputtering

Present study



FeCrAl sputtering

Seo et al., 2016



Results and discussion

- **Model comparison**

① Kandlikar's model

Modeling parameter

- Receding contact angle (β_r) (partial wetting)

$$q_c'' = h_{fg}\rho_g^{1/2}\left(\frac{1+\cos\beta}{16}\right)\left[\frac{2}{\pi}+\frac{\pi}{4}(1+\cos\beta)\cos\phi\right]^{1/2}\times\left[\sigma g\left(\rho_l-\rho_g\right)\right]^{1/4}$$

② Chu et al.'s model (textured)

Modeling parameter

- Receding contact angle (β_r) (complete wetting)
- Roughness factor ($r=r_{micro}xr_{nano}$)

$$q_c'' = K\times h_{fg}\rho_g^{1/2}\times\left[\sigma g\left(\rho_l-\rho_g\right)\right]^{1/4}$$

$$K=\left(\frac{1+\cos\beta}{16}\right)\left[\frac{2(1+\alpha)}{\pi(1+\cos\beta)}+\frac{\pi}{4}(1+\cos\beta)\cos\psi\right]^{1/2}$$

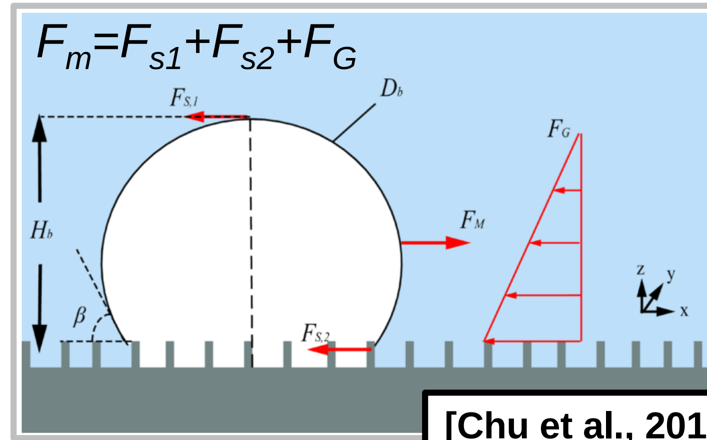
③ Quan et al.'s model (textured)

Modeling parameter

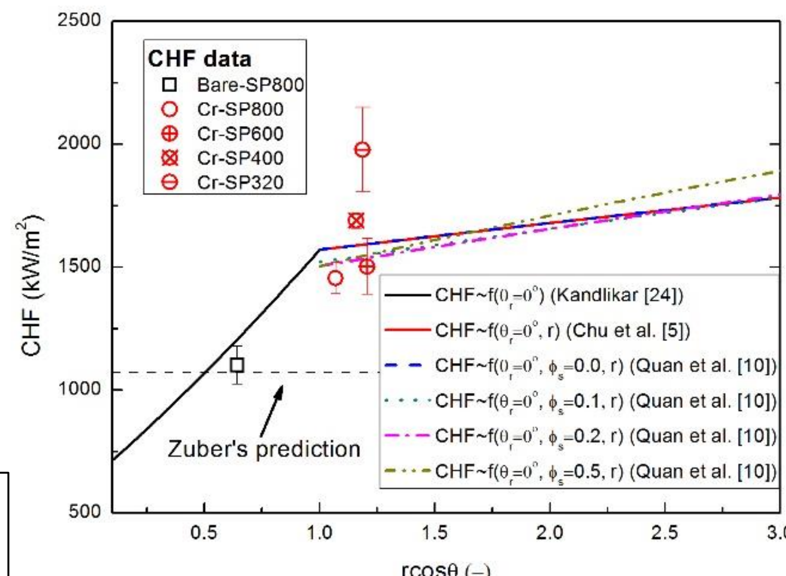
- Receding contact angle (β_r) (complete wetting)
- Roughness factor ($r=r_{micro}xr_{nano}$)
- Solid fraction (ϕ_s)

$$K_{Quan}=\left(\frac{1+\cos\theta_r}{16}\right)\left[\frac{2}{\pi}\left(1-\sqrt{\phi_s}\right)^{-\frac{1}{2}}\frac{r+\cos\theta}{1+\cos\theta}+\frac{\pi}{4}\left(1-\sqrt{\phi_s}\right)^{\frac{1}{2}}\left(1+\cos\theta_r\right)\cos\psi\right]^{1/2}$$

Conventional static force balance of Wenzel bubble



[Chu et al., 2013]



Results and discussion

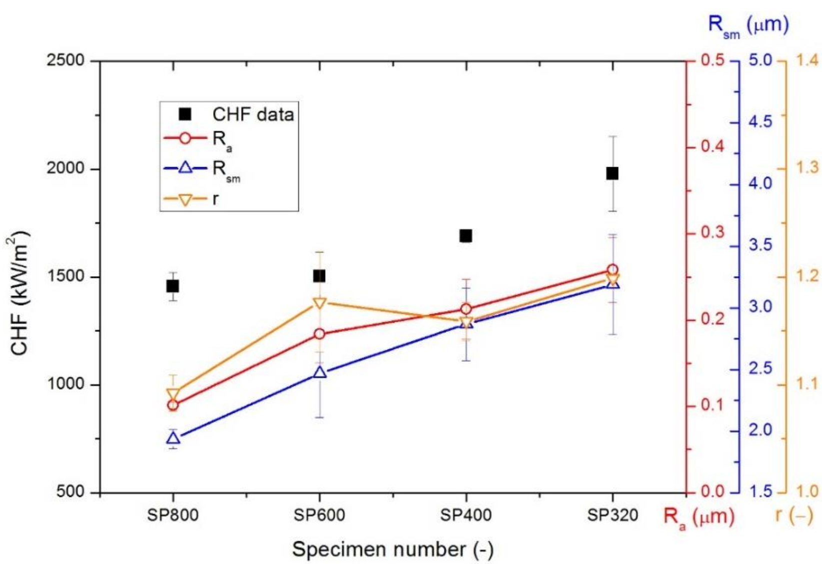
- **Limit of roughness factor estimation on polished surfaces**

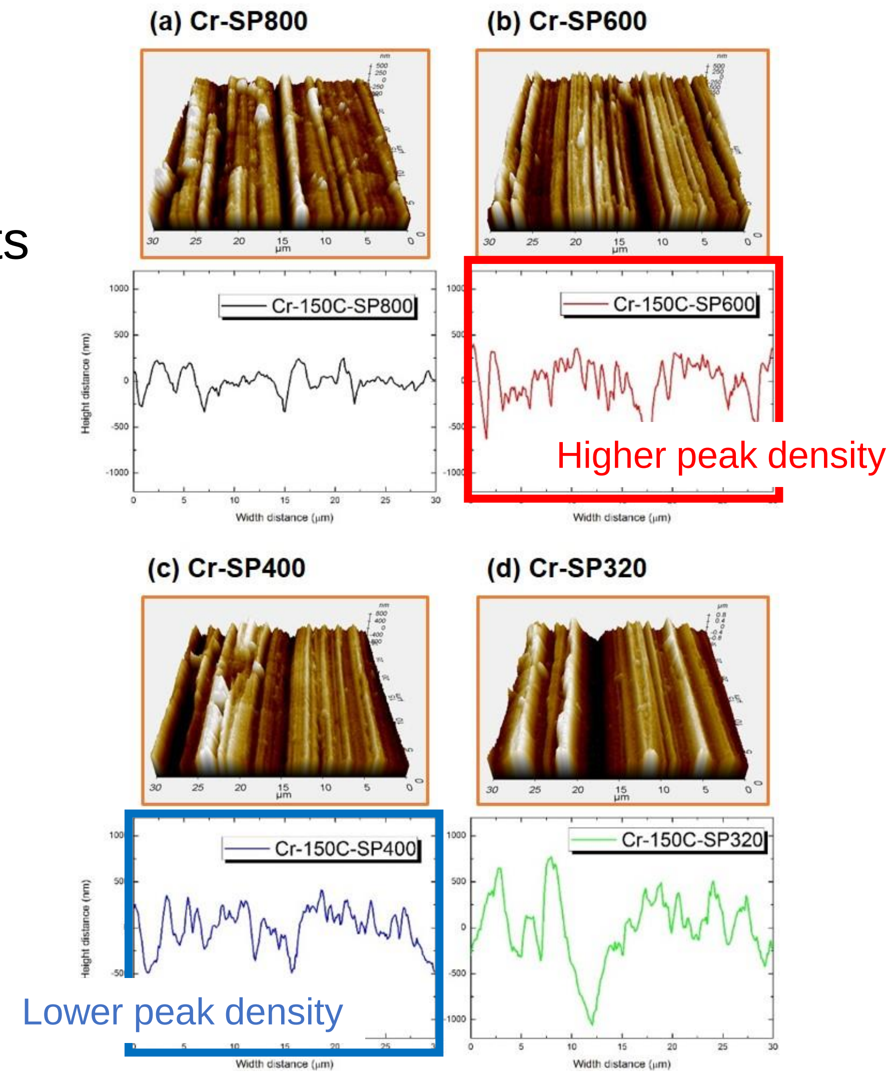
✓ **R_a** and **R_{sm}**: monotonic increase

✓ **r**: non-monotonic increase

✓ Surface area ratio **r** hardly represents monotonic CHF increase

✓ Sometimes lower roughness shows higher surface area ratio



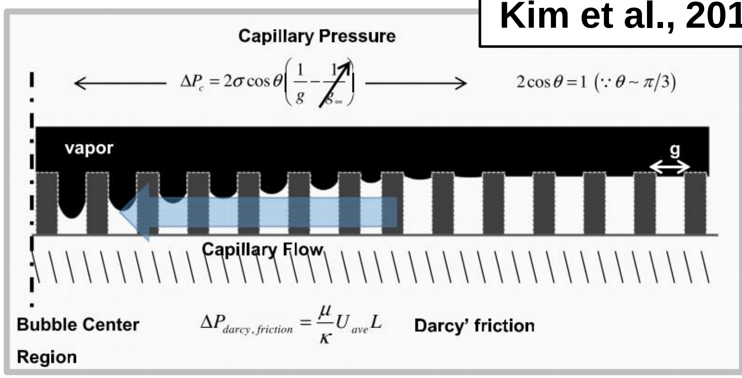


Results and discussion

- **Better approach to capillary wicking flow model instead of conventional static force balance**

Textured surface

Kim et al., 2015



Force balance between capillary and frictional pressures

$$\frac{2\sigma\cos\theta_Y}{g} - \frac{\mu}{\kappa}u_{ave}L = \frac{1}{2}\rho u_{ave}^2$$

Average liquid inflow velocity

$$u_{ave} = -\frac{L}{\kappa}\frac{\mu}{\rho} + \sqrt{\left(\frac{L}{\kappa}\frac{\mu}{\rho}\right)^2 + \frac{1}{2g}\frac{\sigma}{\rho}}$$

Polished surface

Capillary pressure

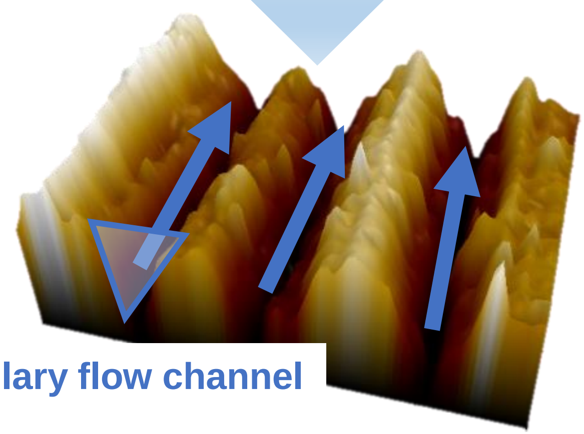
$$P_c = \frac{2\sigma_{lv}\cos\theta}{D_h/2}$$

VS

Viscous frictional pressure

$$P_f = \frac{32\mu u_{avg}}{\phi_s D_h^2}L_t$$

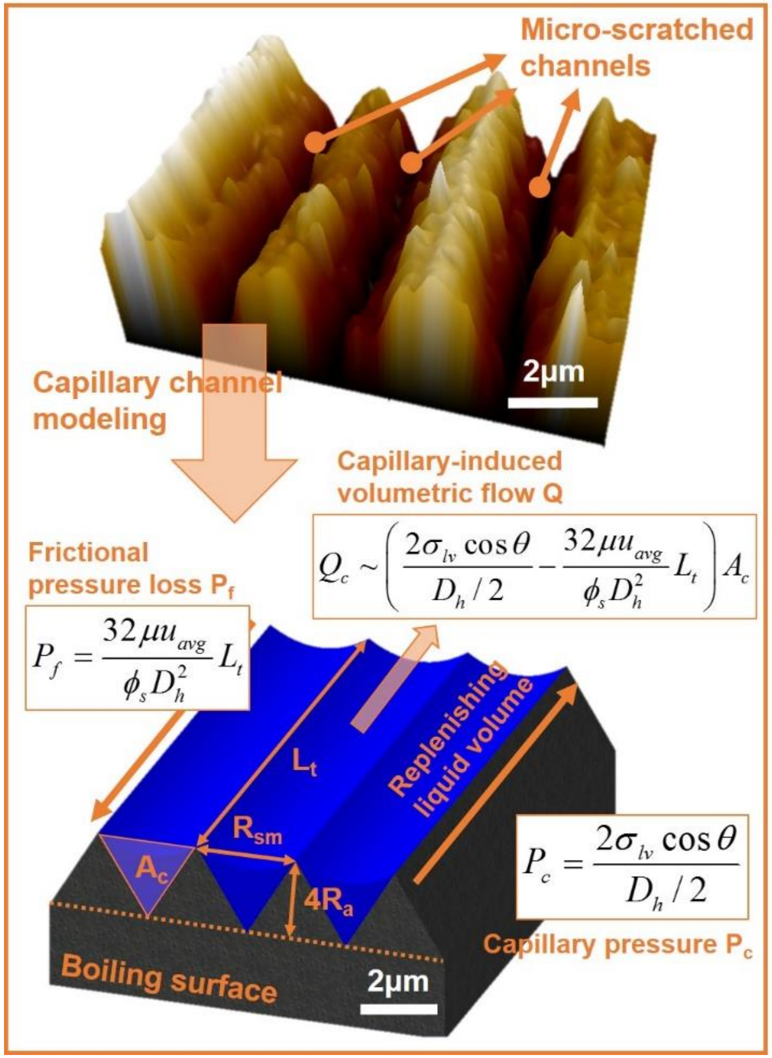
How to define a capillary flow channel on polished surfaces?



Capillary flow channel

Results and discussion

- **Capillary flow channel modeling for the polished surface**



Structural parameters

$$Peak\ \ height = 4R_a$$

$$Peak\ \ pitch = R_{sm}$$

Unit cell parameters

$$A_c = \frac{1}{2}(4R_a)R_{sm}$$

$$p_{wetted} = 2\sqrt{(4R_a)^2 + \frac{1}{4}R_{sm}^2}$$

Hydraulic diameter

$$D_h = \frac{A_c}{p_{wetted}} = \frac{R_a}{\sqrt{\left(4\frac{R_a}{R_{sm}}\right)^2 + \frac{1}{4}}}$$

Results and discussion

- **Model validation**

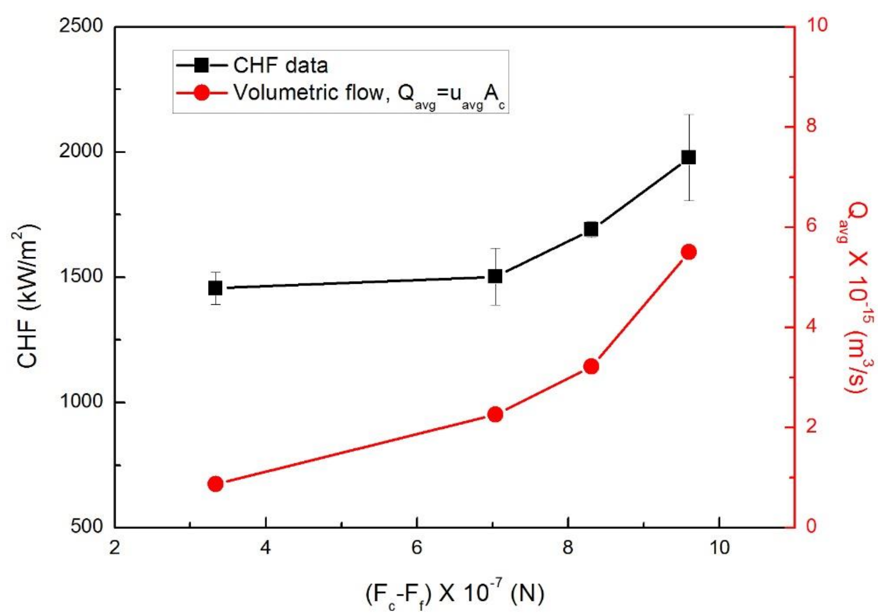
Dynamic wetting properties

Specimen	R_a (μm)	R_{sm} (μm)	R_a/R_{sm} (-)	A_c (μm²)	ϕ_s (-)	D_h (μm)	dD_h/dt (mm/s)	ΔD_h (mm)
Cr-SP800	0.101	1.933	0.052	0.39	0.08	0.18	2.23	0.47
Cr-SP600	0.183	2.467	0.074	0.90	0.16	0.31	2.50	0.53
Cr-SP400	0.213	2.868	0.074	1.22	0.16	0.36	2.63	0.49
Cr-SP320	0.258	3.189	0.080	1.64	0.19	0.43	3.34	0.60

Modified capillary flow model for polished surfaces

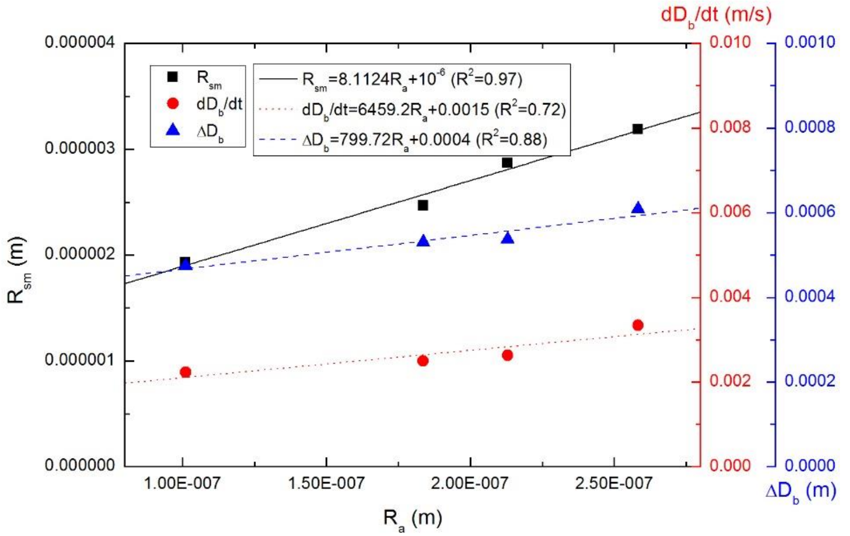
$$q''_{CHF} \sim \left(\frac{2\sigma_{lv}\cos\theta}{D_h/2} - \frac{32\mu \frac{dD_b}{dt}}{\phi_s D_h^2} \Delta D_b \right) A_c$$

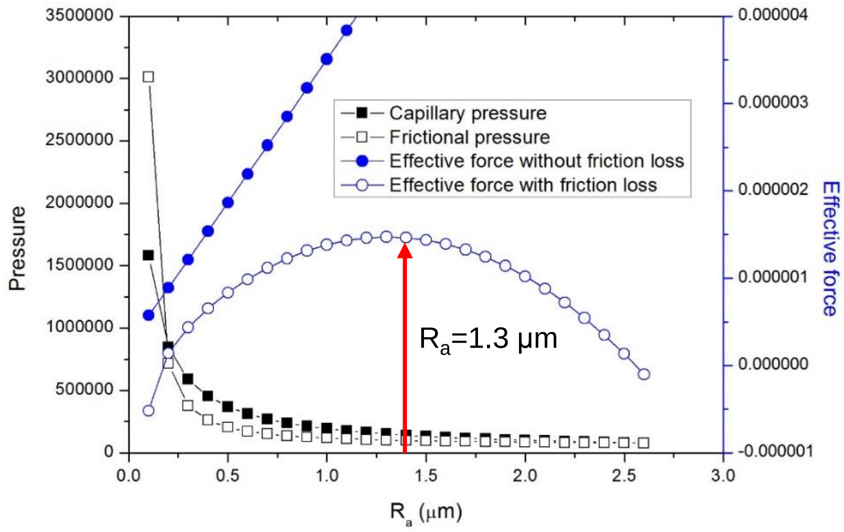
$$D_h = \frac{A_c}{p_{wetted}} = \frac{\frac{1}{2}(4R_a)R_{sm}}{2\sqrt{(4R_a)^2 + \frac{1}{4}R_{sm}^2}}$$



Results and discussion

- **Further estimation of R_a on CHF limit of polished superhydrophilic surface**
  - ✓Assumption: linear approximation of R_a with R_{sm}, dD_b/dt, and ΔD_b
  - ✓Critical limit of R_a=1.3 μm → Spacing (R_{sm}) ~ 11.5 μm
  - ✓Dhillon et al.'s estimation: Spacing ~ 10 μm





Summary and Conclusions

- In this study…
  - ✓ Surface modification: thin film deposition of 1 μm Cr layer
  - ✓ Surface characteristic: superhydrophilic (liquid droplet spreading)
  - ✓ CHF: enhanced up to 79 % within 0.3 μm R_a
- Major findings
  - ✓ Roughness factors for polished surfaces
    : hardly predict the CHF trend
  - ✓ Better CHF prediction
    : capillary wicking force balance instead of conventional static force balance

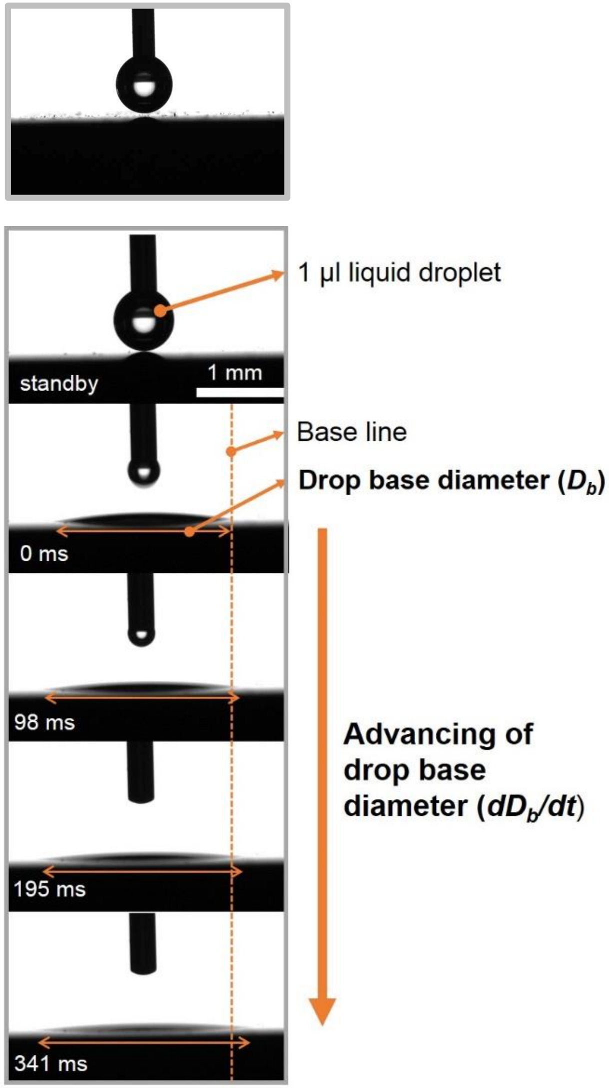
$$D_h = \frac{A_c}{p_{wetted}} = \frac{\frac{1}{2}(4R_a)R_{sm}}{2\sqrt{(4R_a)^2 + \frac{1}{4}R_{sm}^2}} \qquad q''_{CHF} \sim \left(\frac{2\sigma_{lv}\cos\theta}{D_h/2} - \frac{32\mu \frac{dD_b}{dt}}{\phi_s D_h^2}\Delta D_b \right) A_c$$

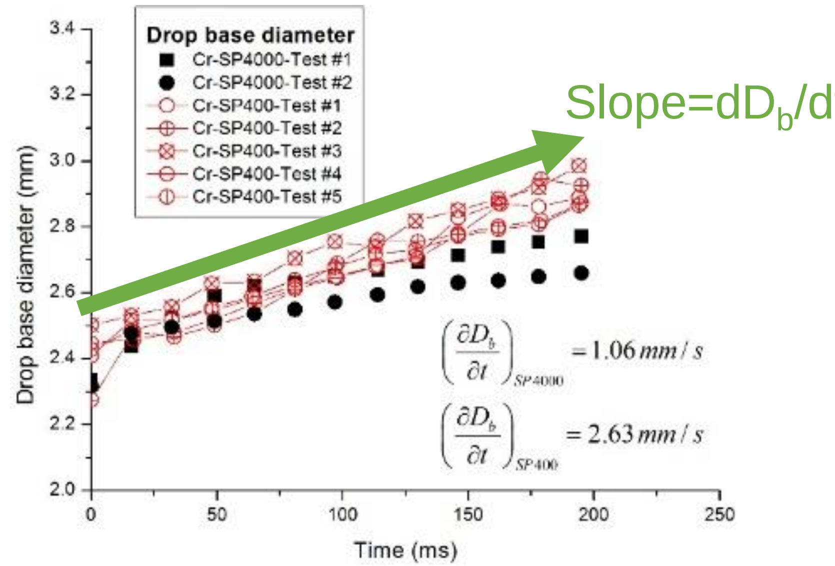
  - ✓ Critical R_{sm} on CHF limit ~ 11.5 μm (for polished superhydrophilic surfaces)

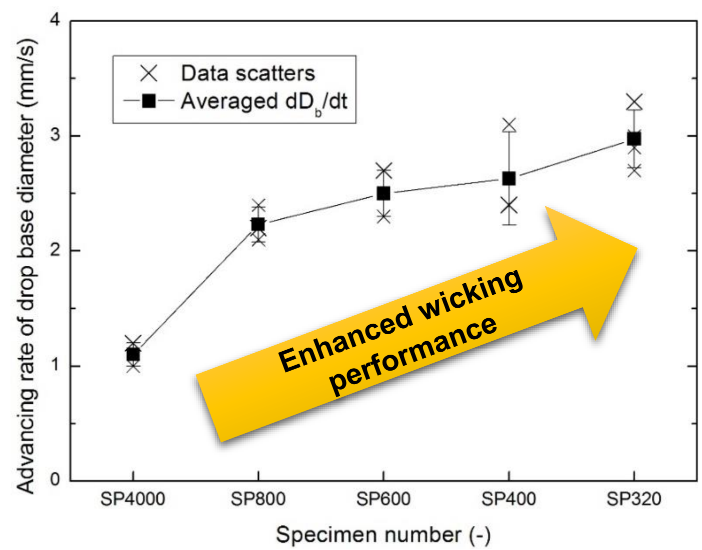
Thank You
for Your
Attention

Surface characteristics

Dynamic wetting

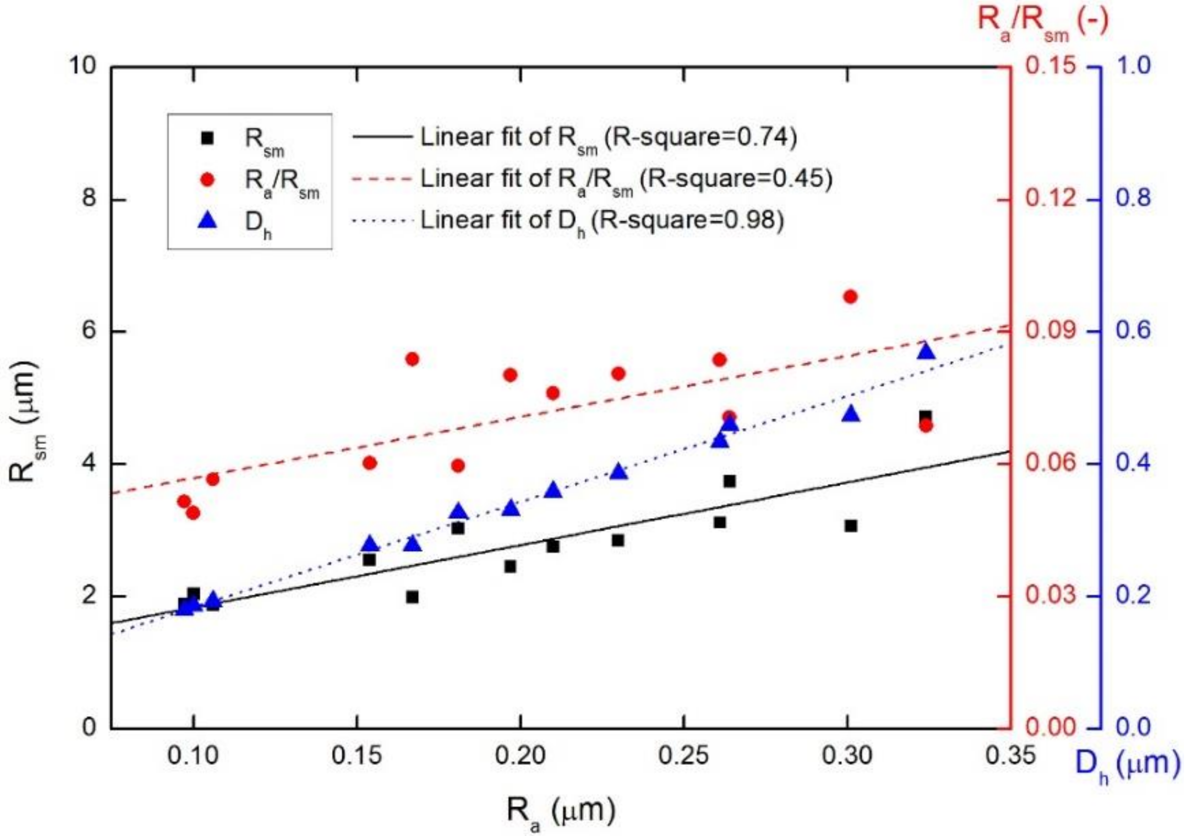






Supplementary

- **Variation of structural parameters** (R_a/R_{sm}, D_h) **calculated using AFM data** (R_a, R_{sm})
  - ✓ **R_a/R_{sm}**: the worst R-square value of 0.45
  - ✓ **D_h**: the best R-square value of 0.98



Supplementary

Single bubble growth in pool boiling