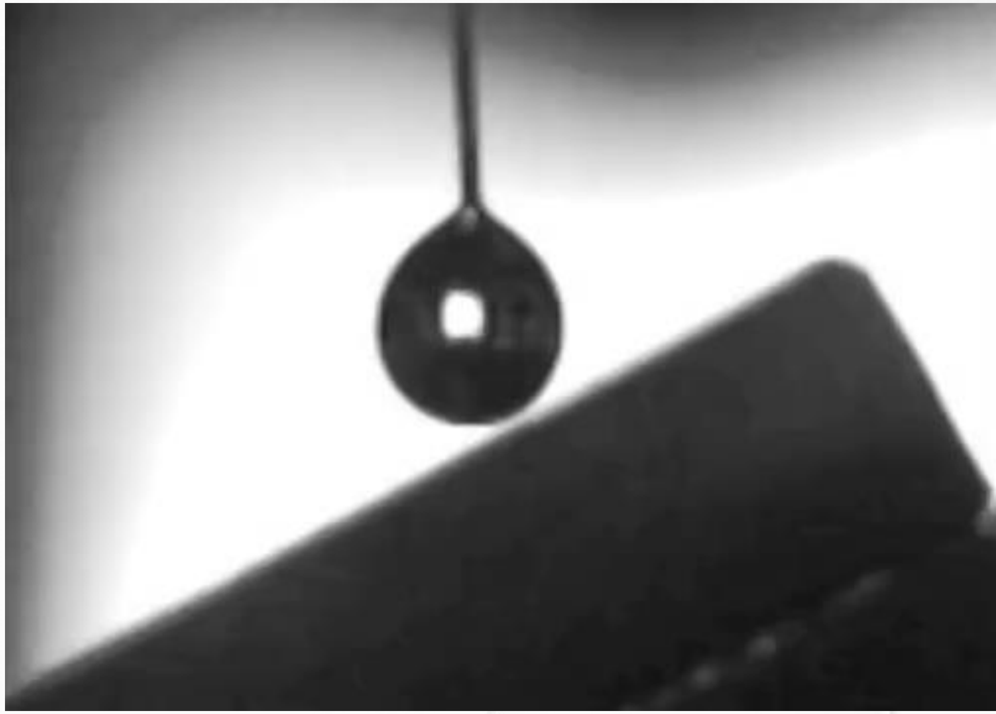
UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

Ministry of Business, Innovation & Employment

The MacDiarmid Institute for Advanced Materials and Nanotechnology

TOPOGRAPHICAL SURFACE TENSION GRADIENTS FOR EFFECTIVE WATER MANAGEMENT IN ENERGY TECHNOLOGY



Kirill Misiiuk
Sam Lowrey, Richard Blaikie,
Andrew Sommers, Geoff Willmott

ONE PLUS THREE

UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

ONE PLUS THREE



ONE PLUS THREE

ONE PLUS THREE

UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

Drop-impact

L. Rampel, Wind Systems Magazine (Issue date 24.10.2012) 22-24]

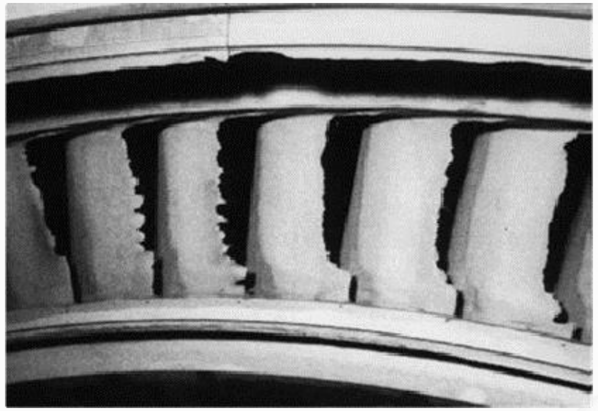
Condensation

David L. Chandler, MIT News Office 21 June 2013

Icing

M. Alrefai, International Conference on Renewable Energies and Power Quality, 2019

What about coatings?

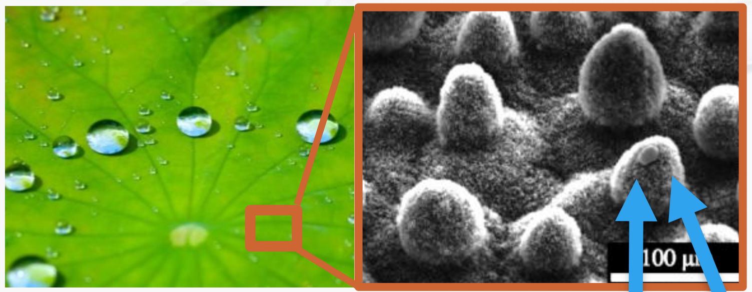


A. Martínez et al., J. energy power eng, 2012, 4 (5), 365-371

Bob Garrard, Aviation Photos (https://www.flickr.com/people/23032926@N05/)

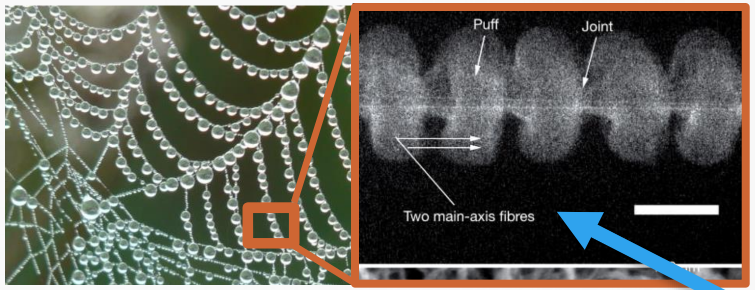
IN THE PREVIOUS EPISODE…

"Lotus effect"

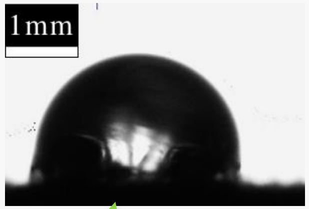


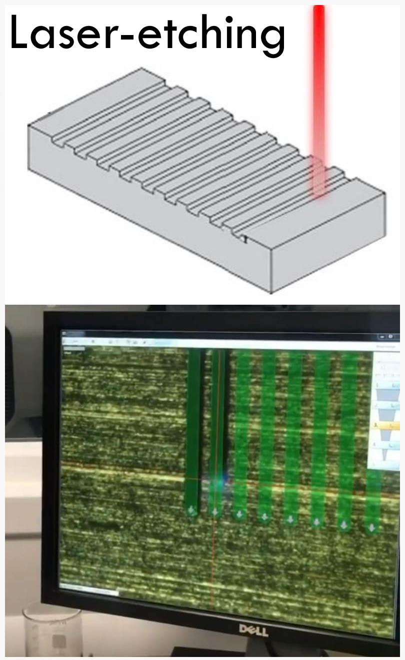
H. Zhang et al., Colloids Surf A: Physicochem. Eng. Aspects, 413, 2012

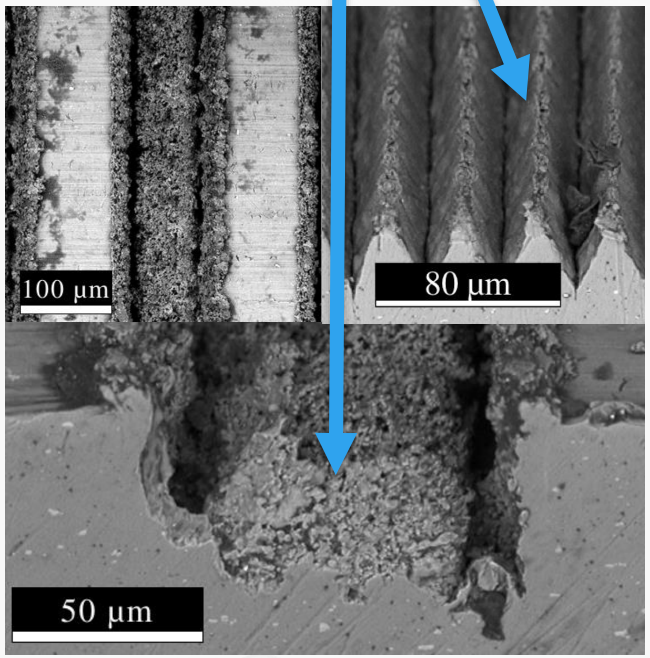
Spider silk



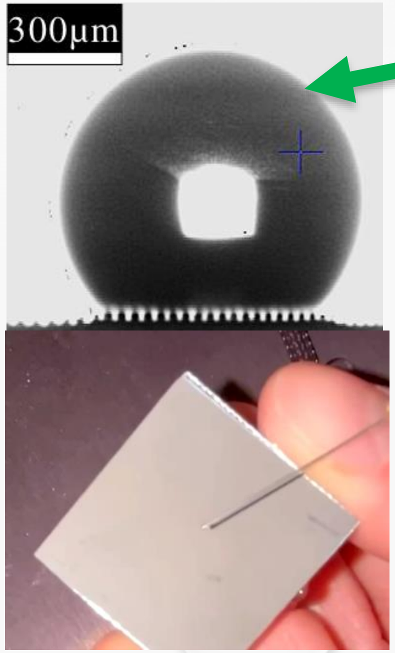
Y. Zheng et al., Nature, 2010



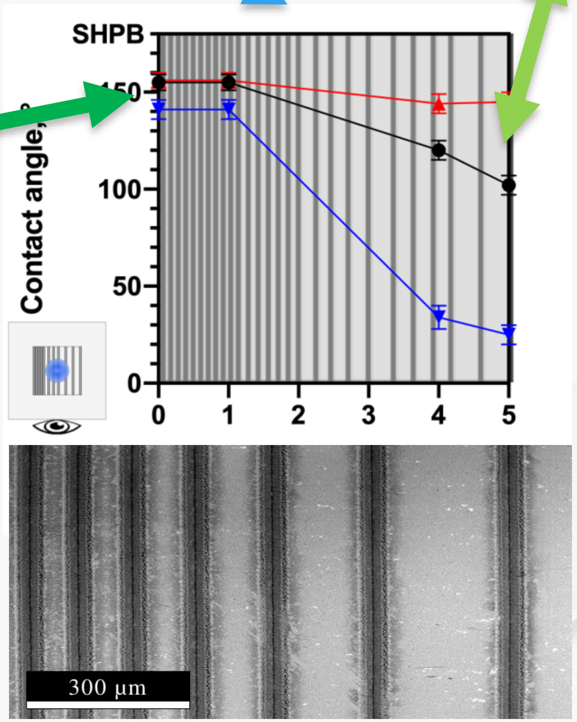




K. Misiiuk et al., Langmuir, 2022
DOI:10.1021/acs.langmuir.1c02517



No coatings!



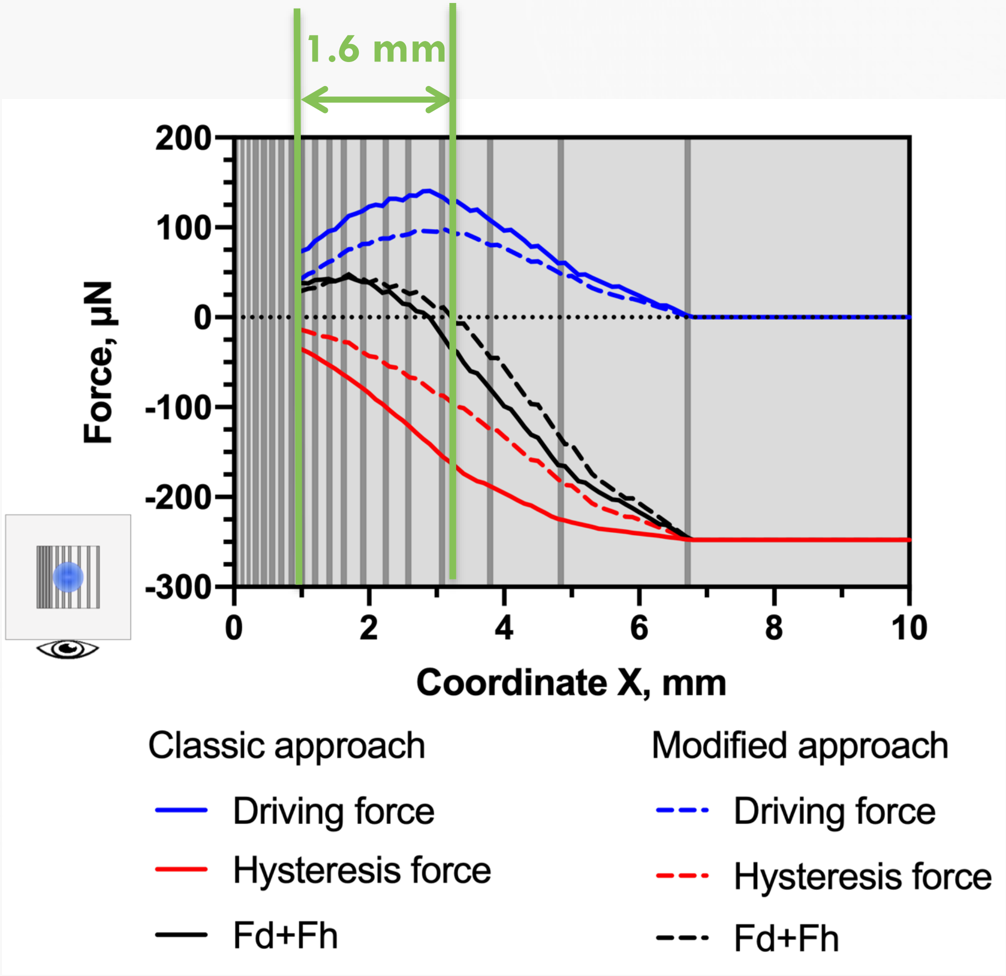
K. Misiiuk et al., Langmuir, 2022
DOI:10.1021/acs.langmuir.1c02518

IN THE PREVIOUS EPISODE…

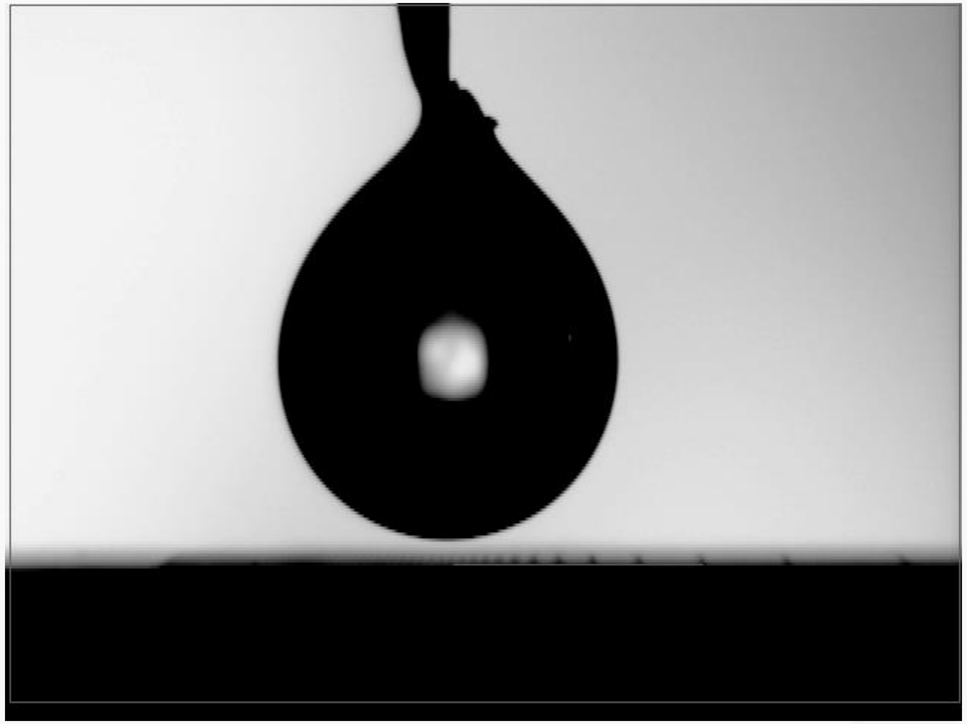
$$F_{acting} = F_{driving} + F_{hysteresis} = 0$$

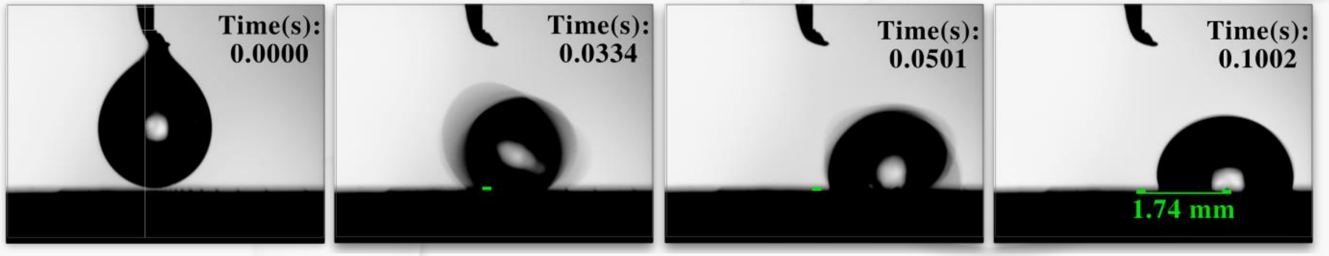
$$\Downarrow$$

$$\frac{df}{dx} = \frac{8f_0(\cos\theta_1 - \cos\theta_2)}{D_{FP}[(\cos\theta_2 + 1)(4+\pi) - (\cos\theta_1 + 1)(4-\pi)]}$$



Working principle for 8 µL droplet

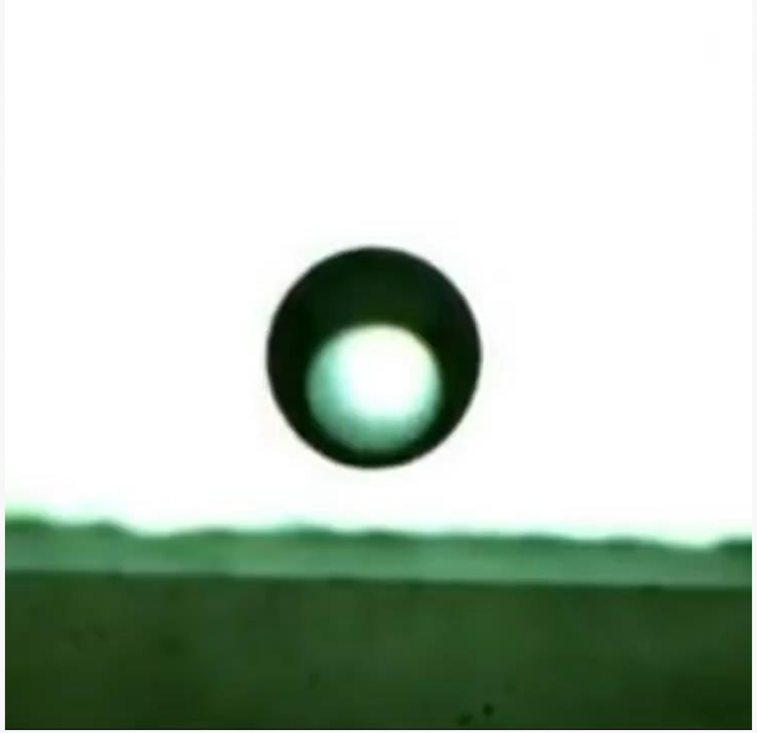




1.74 mm

K. Misiiuk et al., Langmuir, 2022, DOI:10.1021/acs.langmuir.1c02518

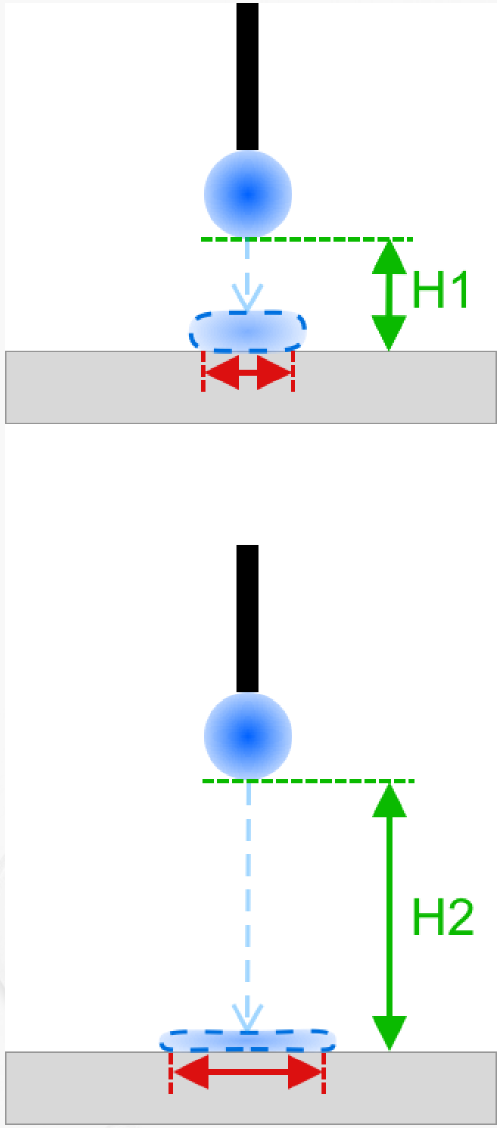
CURRENT STAGE: DROP IMPACT



University of Missouri, MUEngineering, https://youtu.be/riXp_Q-fDv8

During impact the **footprint** is changing!

$$\frac{df}{dx} = \frac{8f_0(\cos\theta_1 - \cos\theta_2)}{\boxed{D_{FP}}[(\cos\theta_2 + 1)(4+\pi) - (\cos\theta_1 + 1)(4-\pi)]}$$



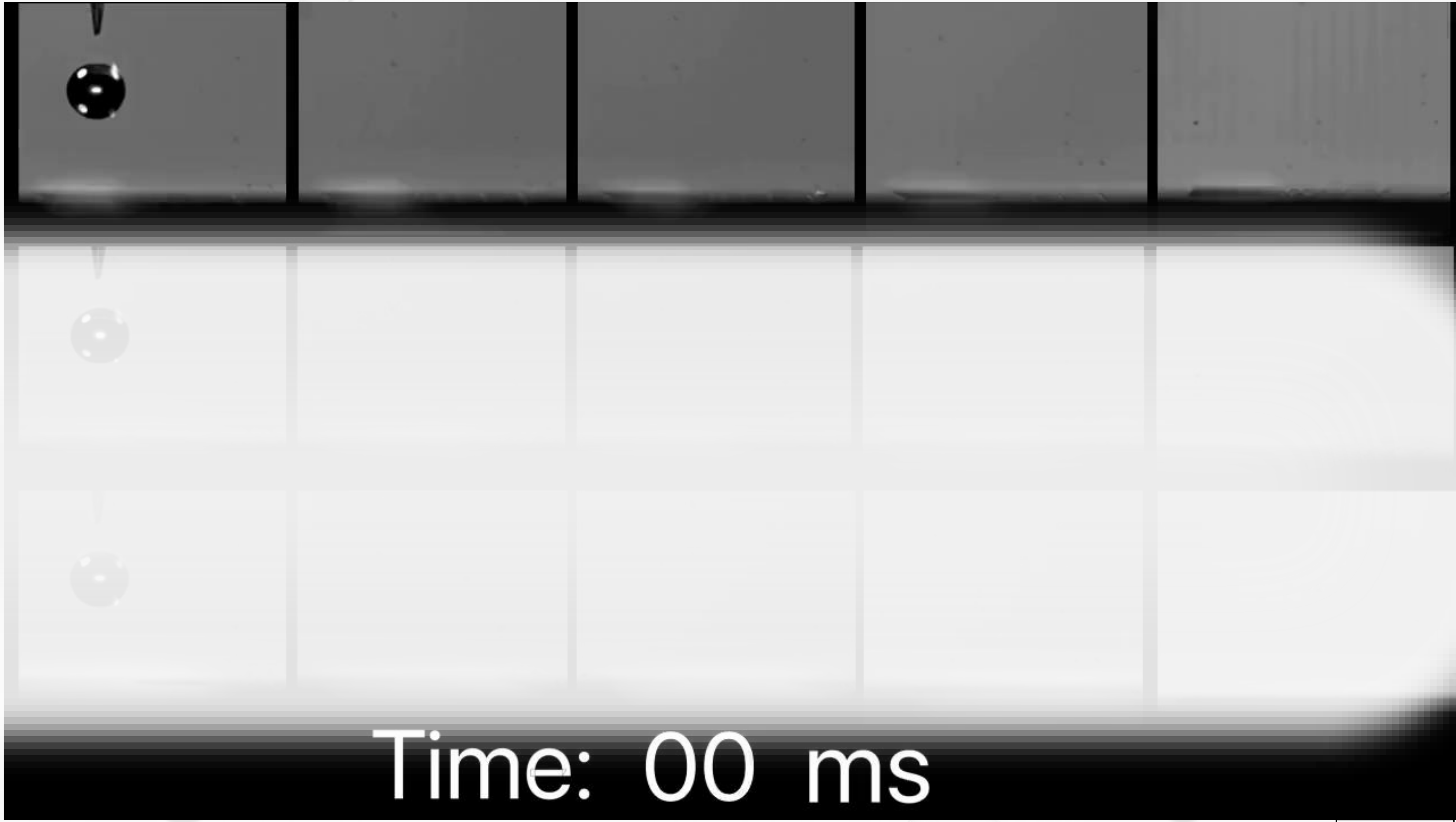
CURRENT STAGE: DROP IMPACT

Impact velocity: 0.3 m/s | 0.6 m/s | 1.0 m/s | 1.4 m/s | 2.0 m/s

Strong gradient (df/dx = 0.24):

Intermediate gradient (df/dx = 0.11):

Weak gradient (almost uniform SHPB, df/dx = 0.08):



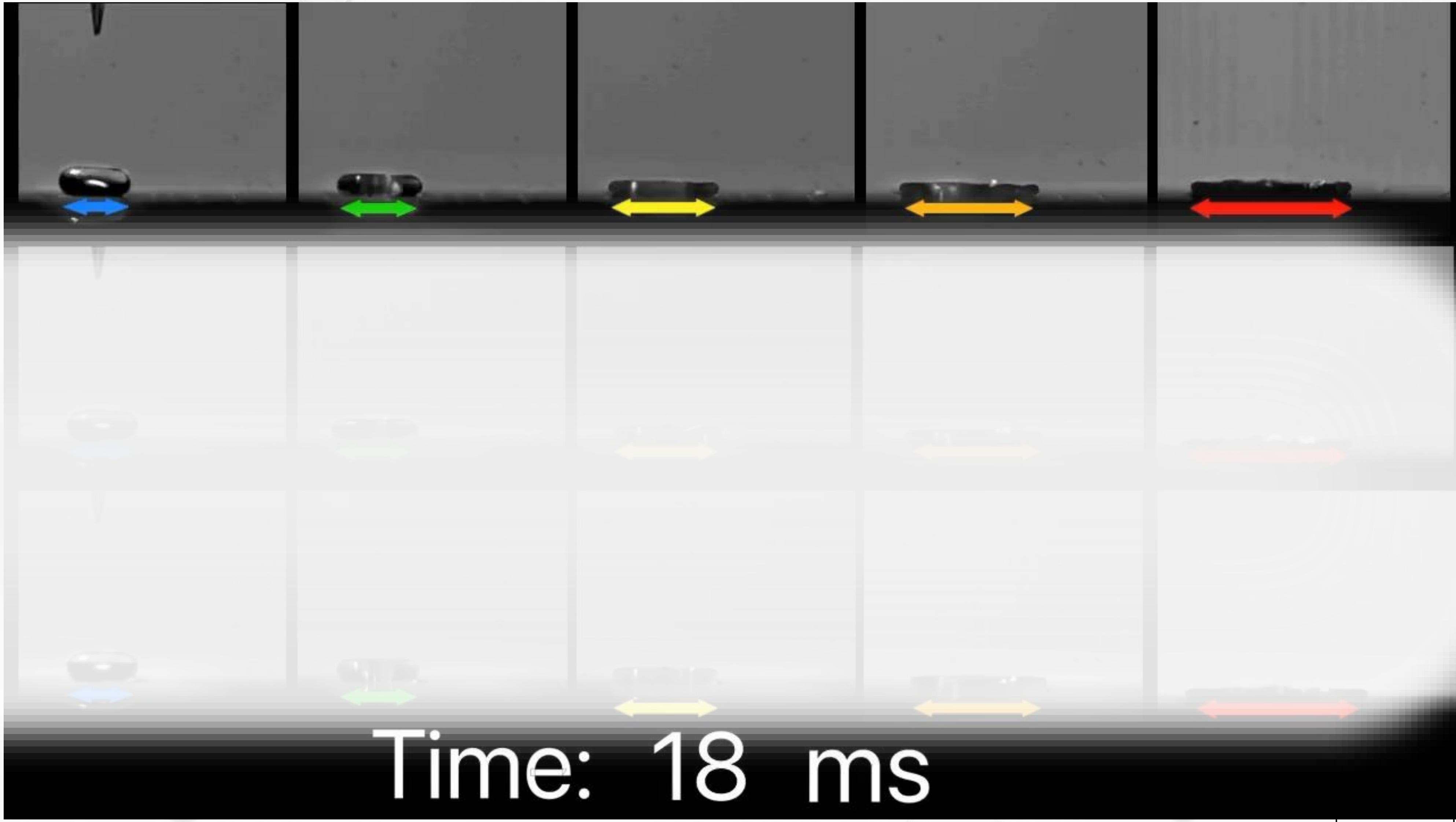
CURRENT STAGE: DROP IMPACT

Impact velocity: 0.3 m/s 0.6 m/s 1.0 m/s 1.4 m/s 2.0 m/s

Strong gradient (df/dx = 0.24):

Intermediate gradient (df/dx = 0.11):

Weak gradient (almost uniform SHPB, df/dx = 0.08):



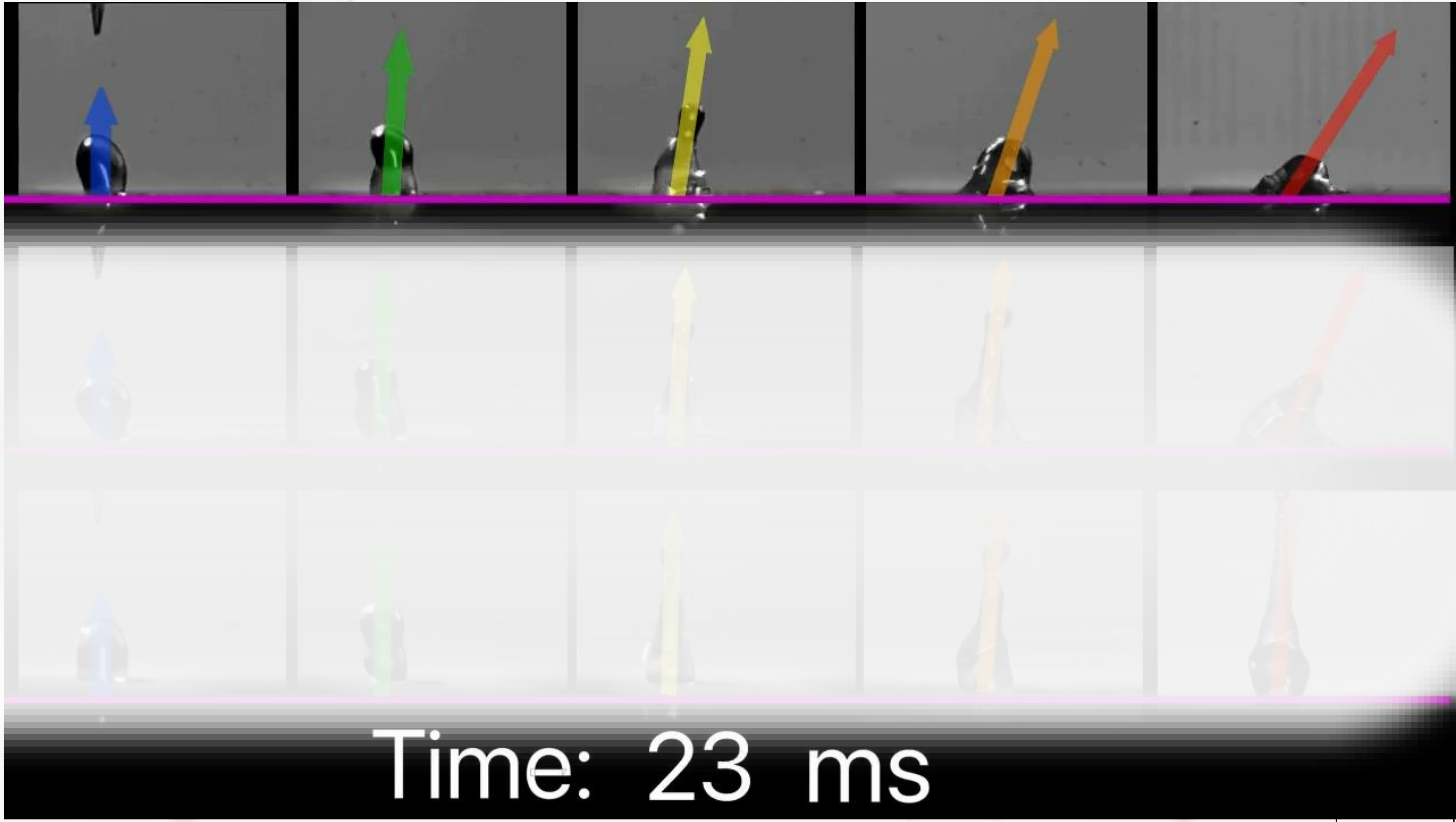
CURRENT STAGE: DROP IMPACT

Impact velocity: 0.3 m/s 0.6 m/s 1.0 m/s 1.4 m/s 2.0 m/s

Strong gradient (df/dx = 0.24):

Intermediate gradient (df/dx = 0.11):

Weak gradient (almost uniform SHPB, df/dx = 0.08):



UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

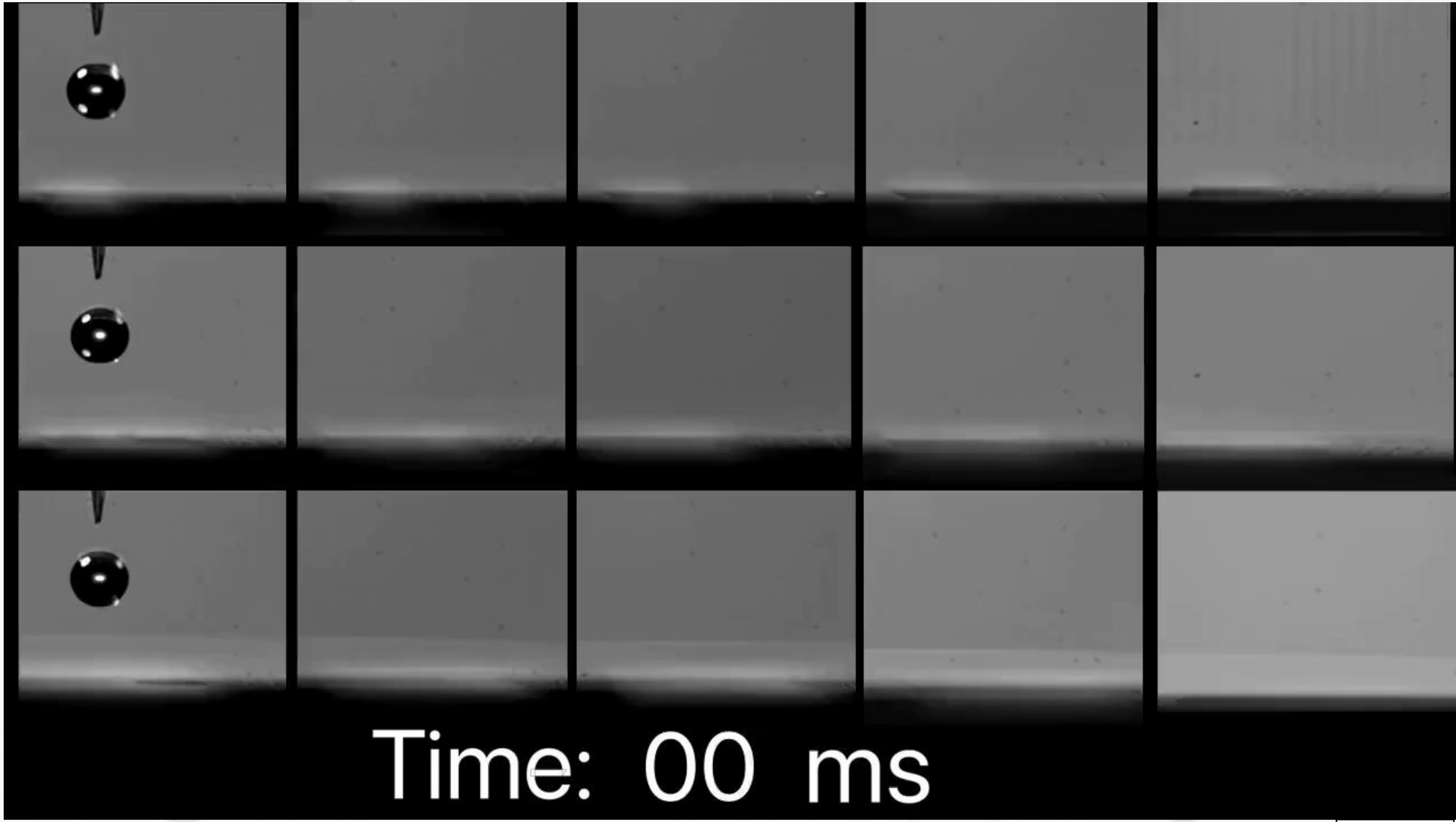
CURRENT STAGE: DROP IMPACT

Impact velocity: 0.3 m/s | 0.6 m/s | 1.0 m/s | 1.4 m/s | 2.0 m/s

Strong gradient (df/dx = 0.24):

Intermediate gradient (df/dx = 0.11):

Weak gradient (almost uniform SHPB, df/dx = 0.08):



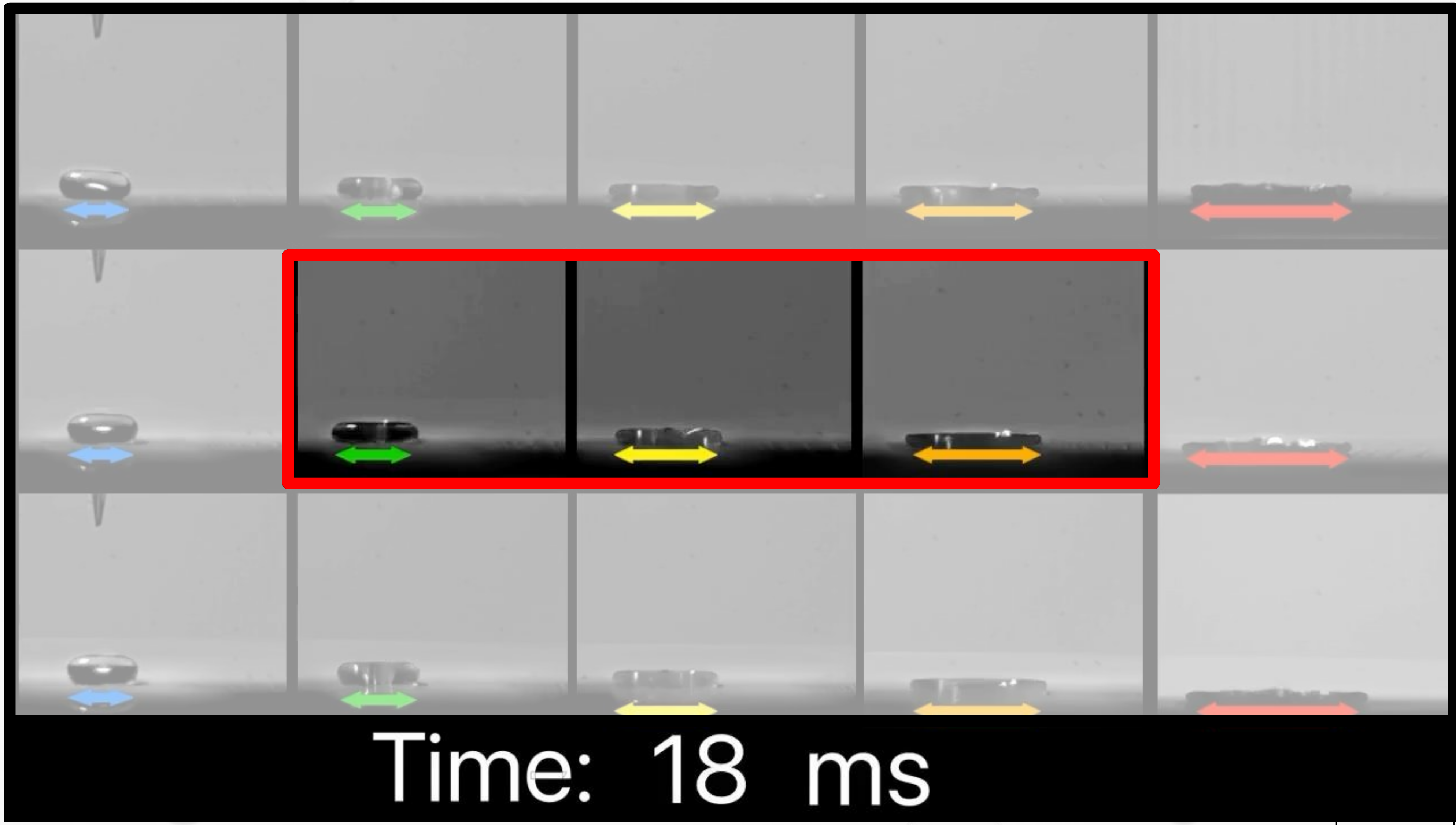
CURRENT STAGE: DROP IMPACT

Impact velocity: 0.3 m/s | 0.6 m/s | 1.0 m/s | 1.4 m/s | 2.0 m/s

Strong gradient (df/dx = 0.24):

Intermediate gradient (df/dx = 0.11):

Weak gradient (almost uniform SHPB, df/dx = 0.08):



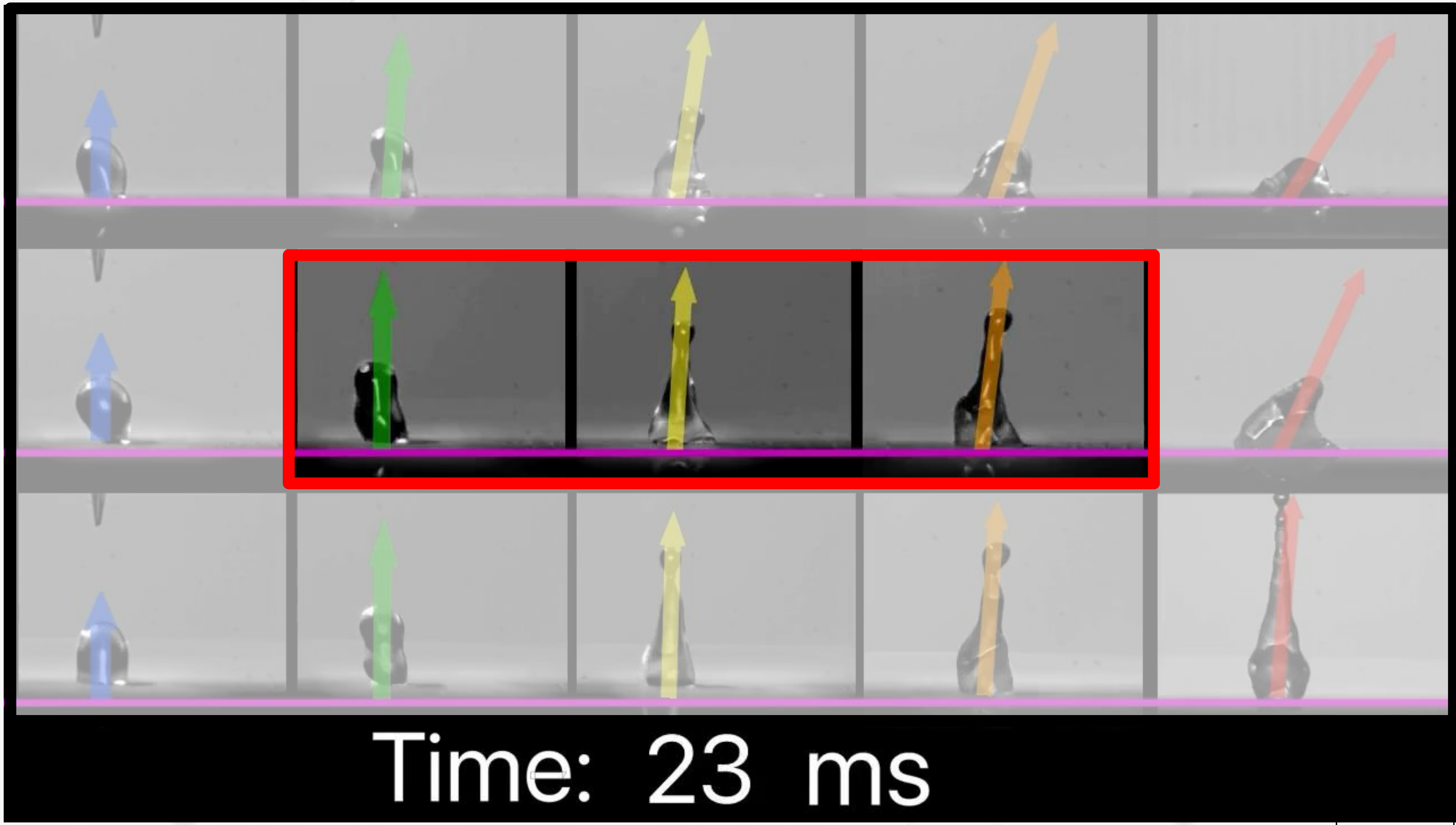
CURRENT STAGE: DROP IMPACT

Impact velocity: 0.3 m/s 0.6 m/s 1.0 m/s 1.4 m/s 2.0 m/s

Strong gradient (df/dx = 0.24):

Intermediate gradient (df/dx = 0.11):

Weak gradient (almost uniform SHPB, df/dx = 0.08):



CURRENT STAGE: DROP IMPACT

Impact velocity: 0.3 m/s | 0.6 m/s | 1.0 m/s | 1.4 m/s | 2.0 m/s

Strong gradient (df/dx = 0.24):

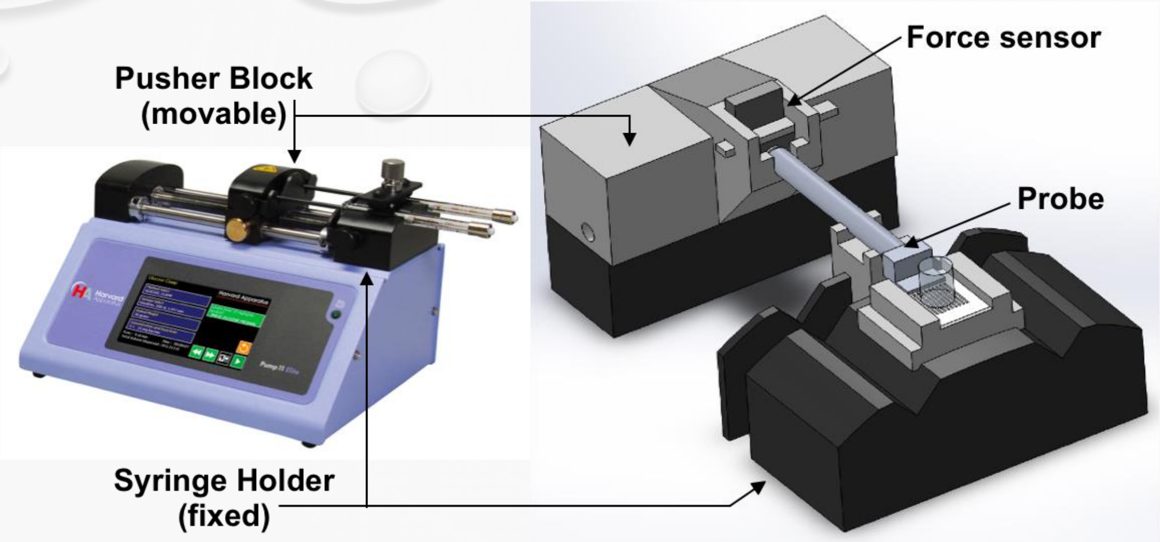
Intermediate gradient (df/dx = 0.11):

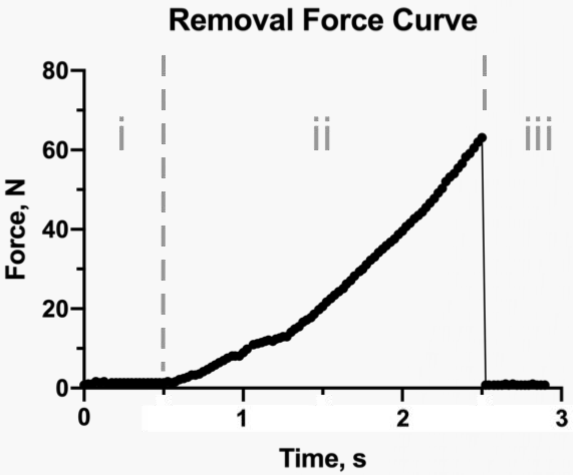
Weak gradient (almost uniform SHPB, df/dx = 0.08):

UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

CURRENT STAGE: ICE ADHESION

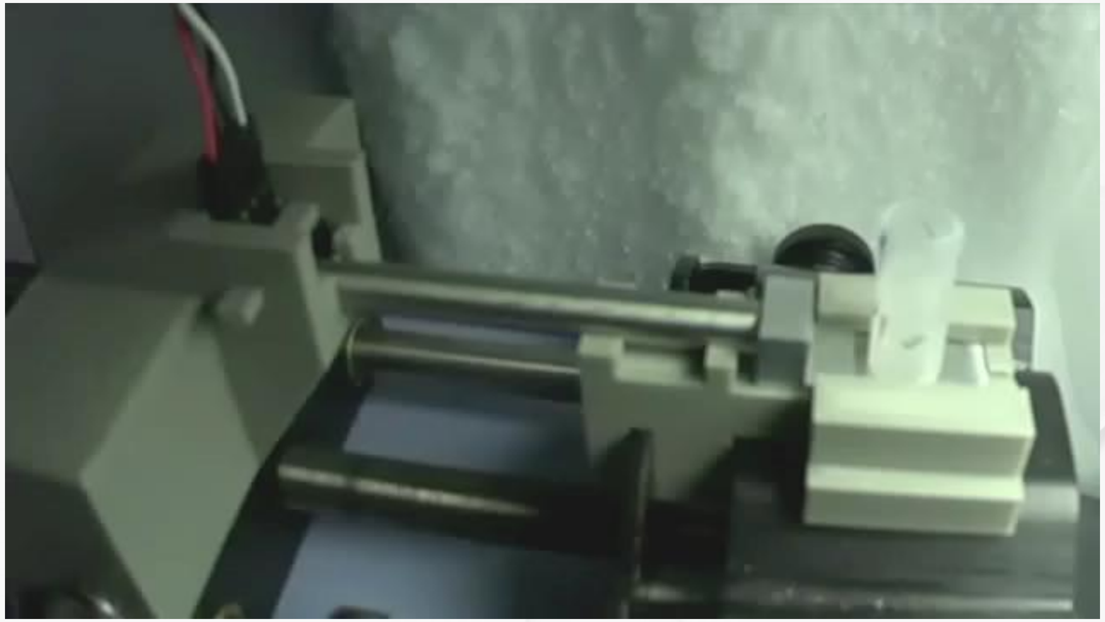
Bryan Preston, PJ Media, 17 February 2021





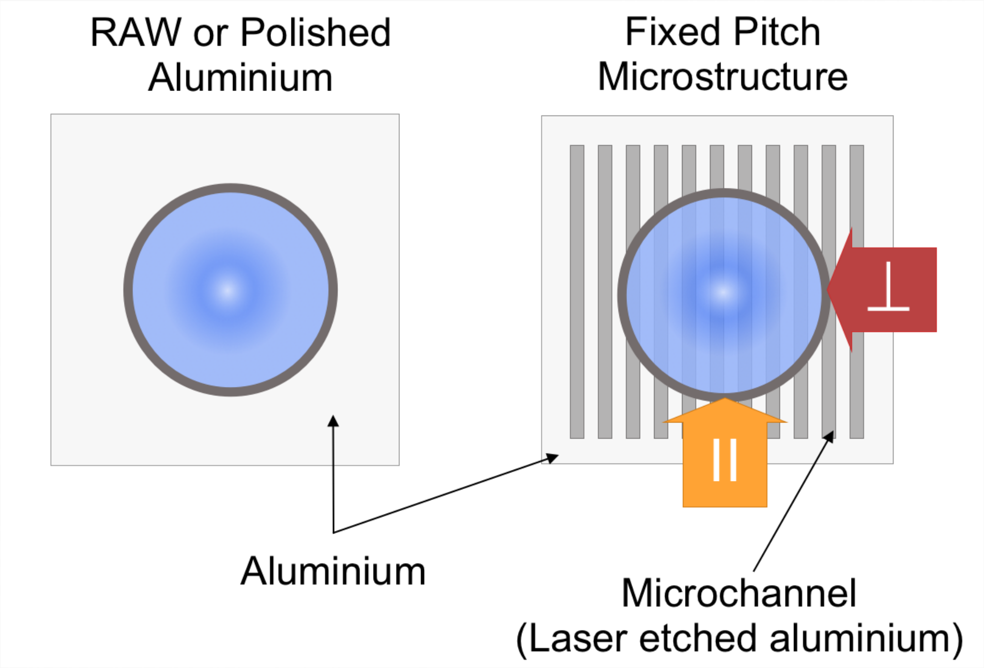
The setup overview ▲

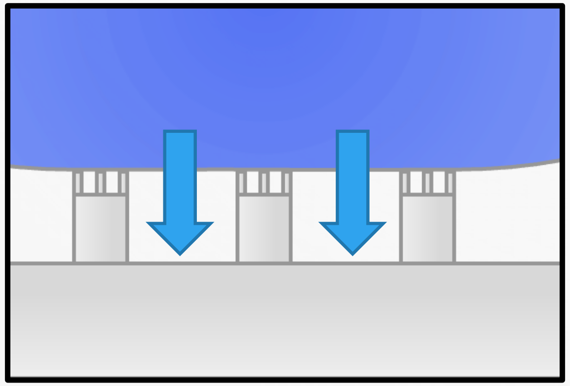
An experiment example (speed up x5) ▶

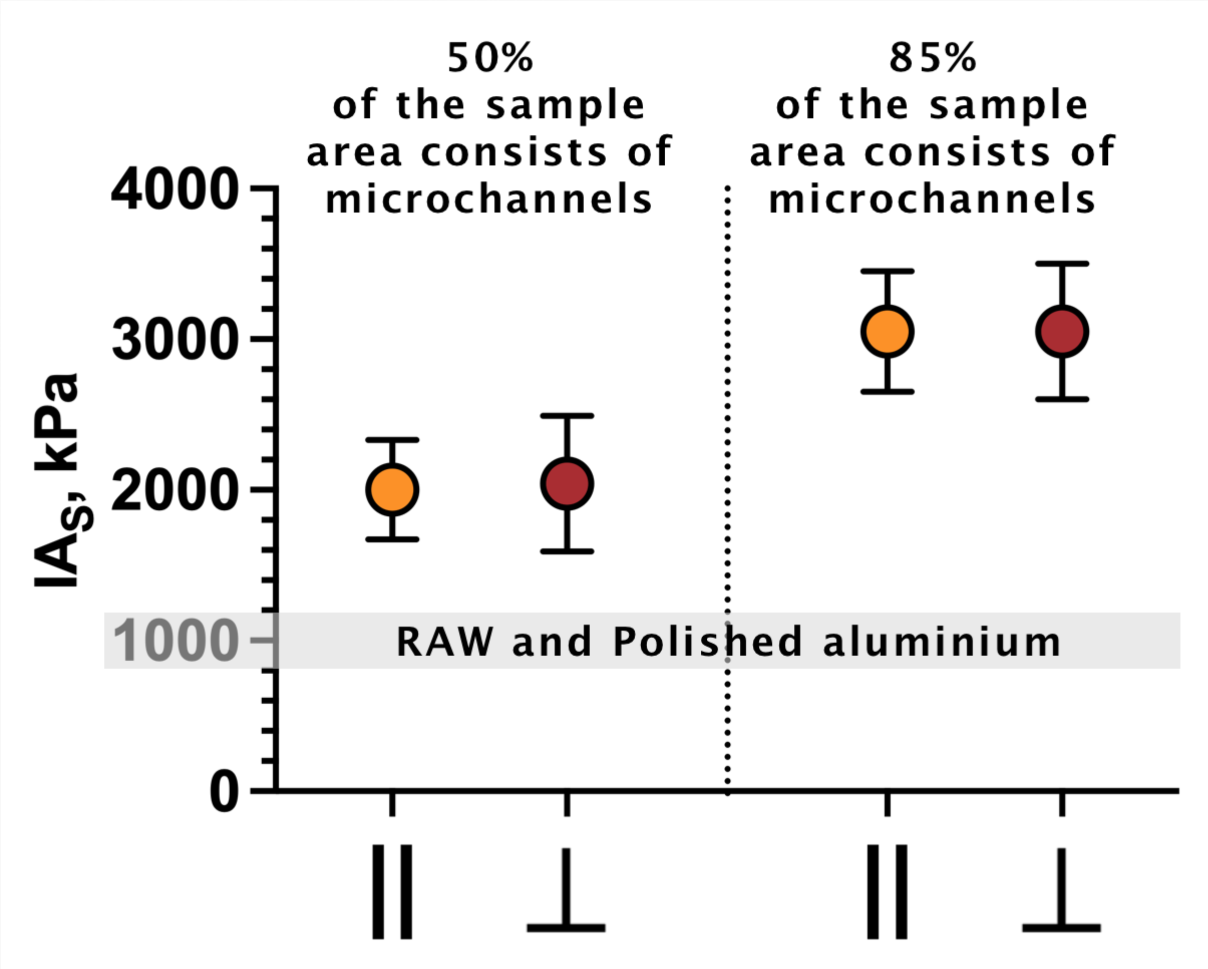


CURRENT STAGE: ICE ADHESION

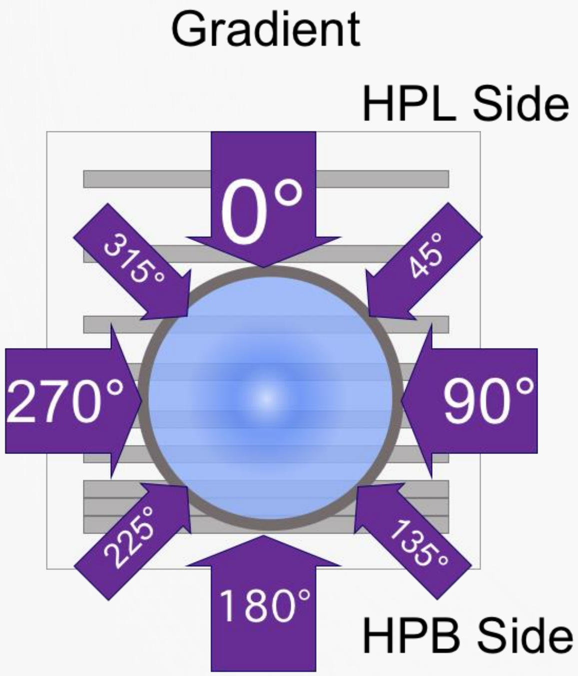
$$IA_s = F/A_{ice-base}$$

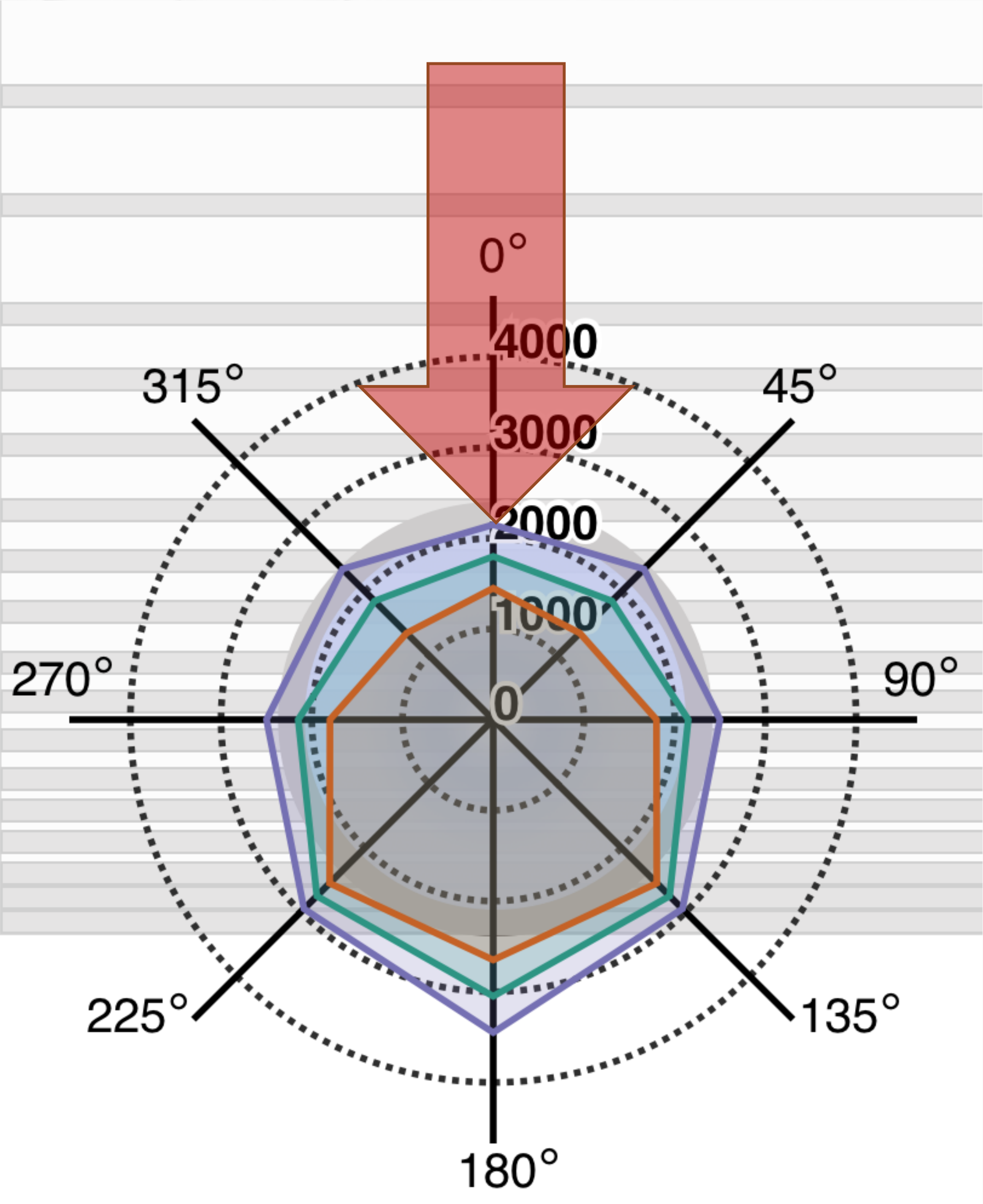






CURRENT STAGE: ICE ADHESION





Pushing from here requires the same force as polished Al!

Colour scheme:

- Mean + Absolute Error
- Mean
- Mean – Absolute Error

UNIVERSITY of OTAGO
SAPERE AUDE
Te Whare Wānanga o Otāgo
NEW ZEALAND

Ministry of Business, Innovation & Employment

The MacDiarmid Institute for Advanced Materials and Nanotechnology

TOPOGRAPHICAL SURFACE TENSION GRADIENTS FOR EFFECTIVE WATER MANAGEMENT IN ENERGY TECHNOLOGY

Waterbending!

- ✓ Gradients provide hydrophobicity;
- ✓ It is possible to control bouncing-off outcome;
- ✓ In case of icing, gradients allow to remove ice at a force similar to unprocessed aluminium;
- ✓ Survived after 100 ice removal cycles;
- ✓ Applicable for various fields;

UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

Ministry of Business, Innovation & Employment

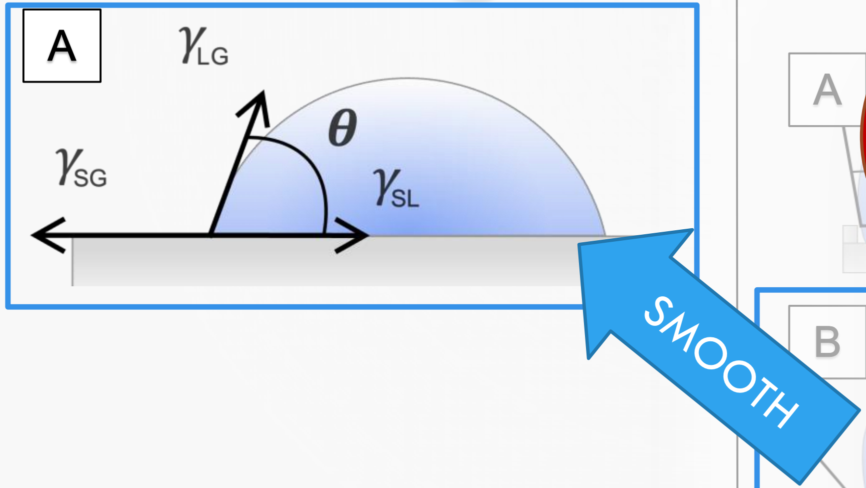
The MacDiarmid Institute for Advanced Materials and Nanotechnology

Kirill Misiiuk
Sam Lowrey, Richard Blaikie,
Andrew Sommers, Geoff Willmott

Thank you for your attention!

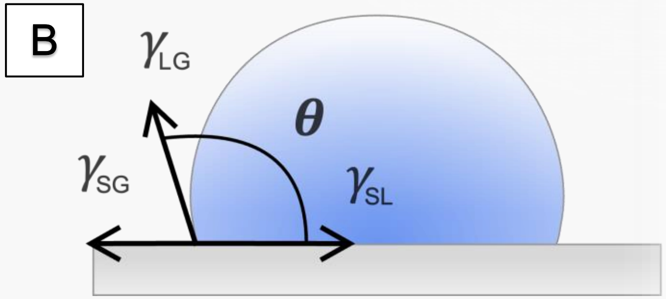
FUNDAMENTALS: STATICS

Solid-liquid interaction



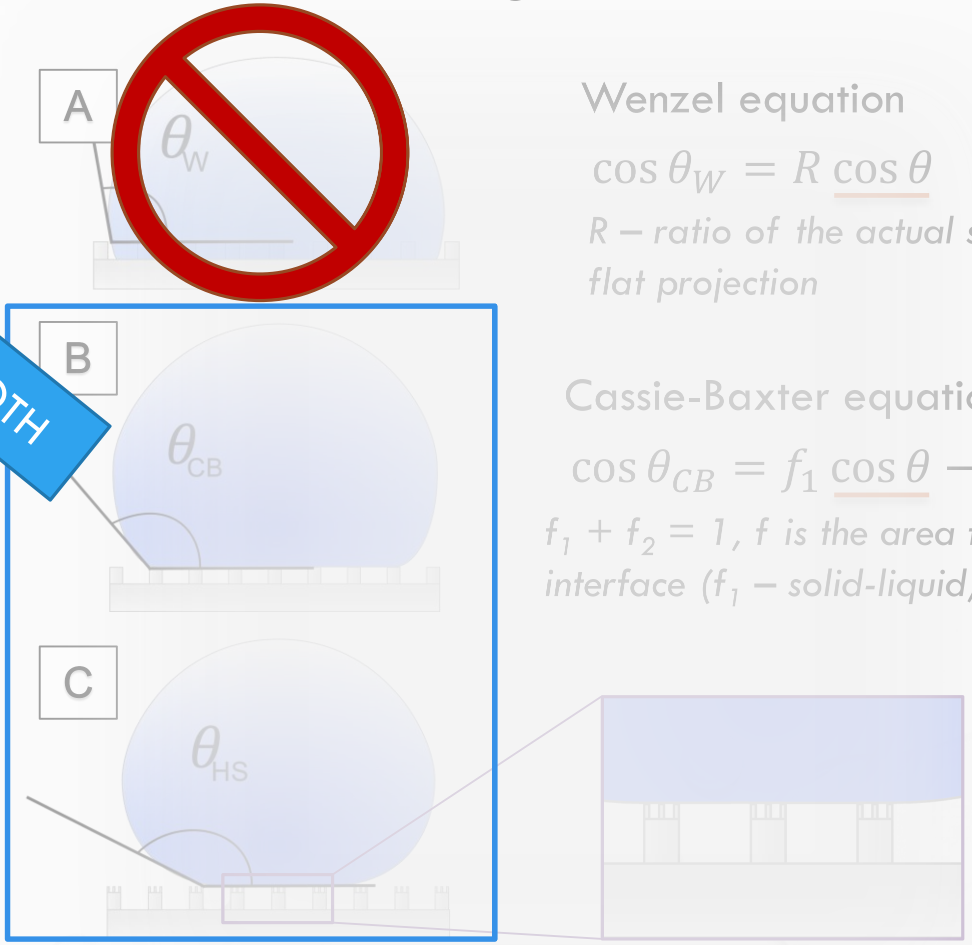
Young's equation

$$\gamma_{SG} = \gamma_{SL} + \gamma_{LG} \cos\theta$$



Contact angle of a flat surface.
(A) hydrophilic (*HPL*, 0°< $\theta \leq$ 90°),
(B) hydrophobic (*HPB*, 90° ≤ θ <180°),

Wetting states



Wenzel equation

$$\cos\theta_W = R\cos\theta$$

R – ratio of the actual surface to the flat projection

Cassie-Baxter equation

$$\cos\theta_{CB} = f_1\cos\theta - f_2$$

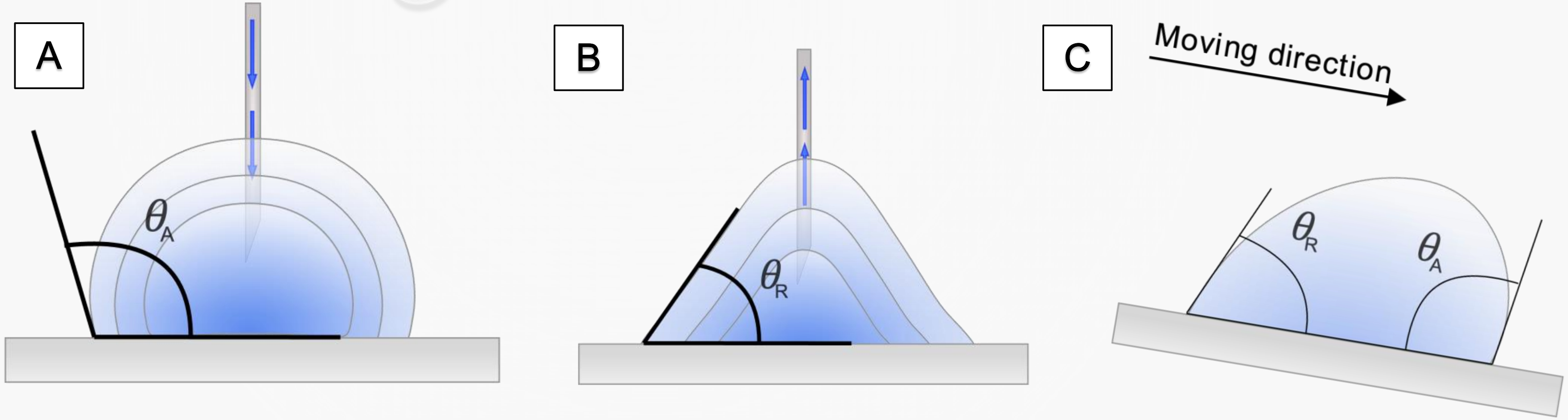
$f_1 + f_2 = 1$, f is the area fraction of an interface (f_1 – solid-liquid, f_2 – liquid-air)

An illustration of the differences of contact models:
(A) Wenzel's model,
(B) Cassie-Baxter's model,
(C) Hierarchical structure with CB-CB states.

FUNDAMENTALS: DYNAMICS

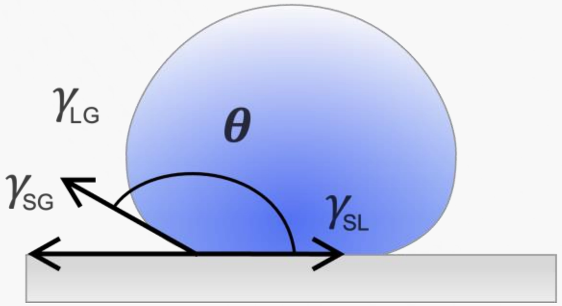
Contact angle hysteresis

$$CAH = \theta_A - \theta_R$$



Schematic of a contact angle hysteresis measurement by (A) increasing and (B) decreasing of a droplet volume; (C) “tilting plate”-method, where a droplet is moving over the surface.

$$\theta_R \leq \theta \leq \theta_A$$

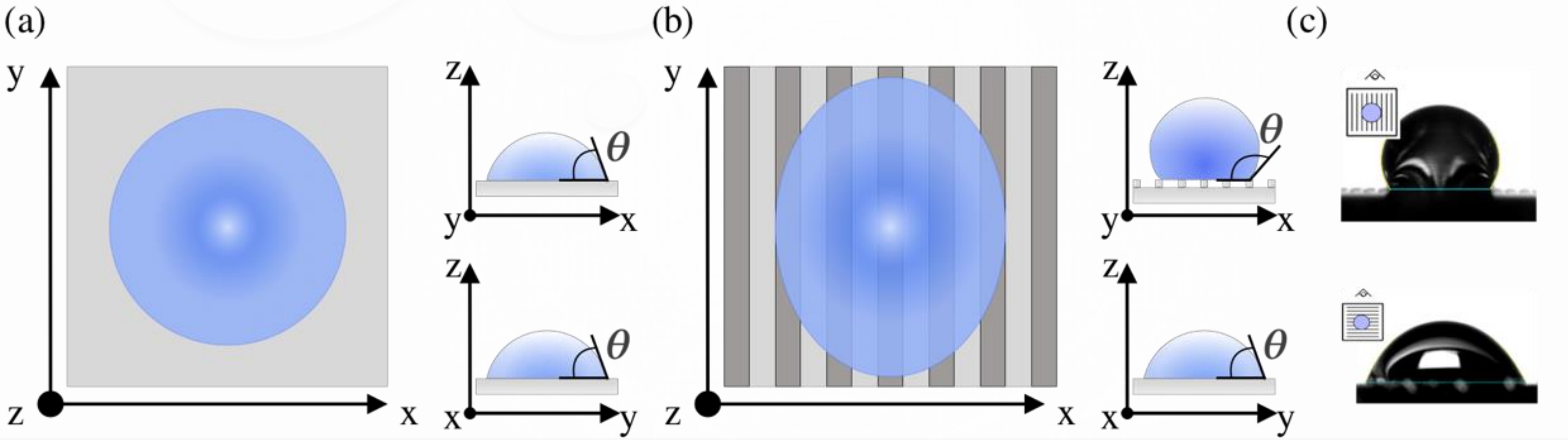


Criteria of superhydrophobicity:

CA (θ) ≥ 150°, ← Less interaction with the surface

CAH ≤ 15° ← Easy to slide/roll off

FUNDAMENTALS: MICRO-WETTING STATE

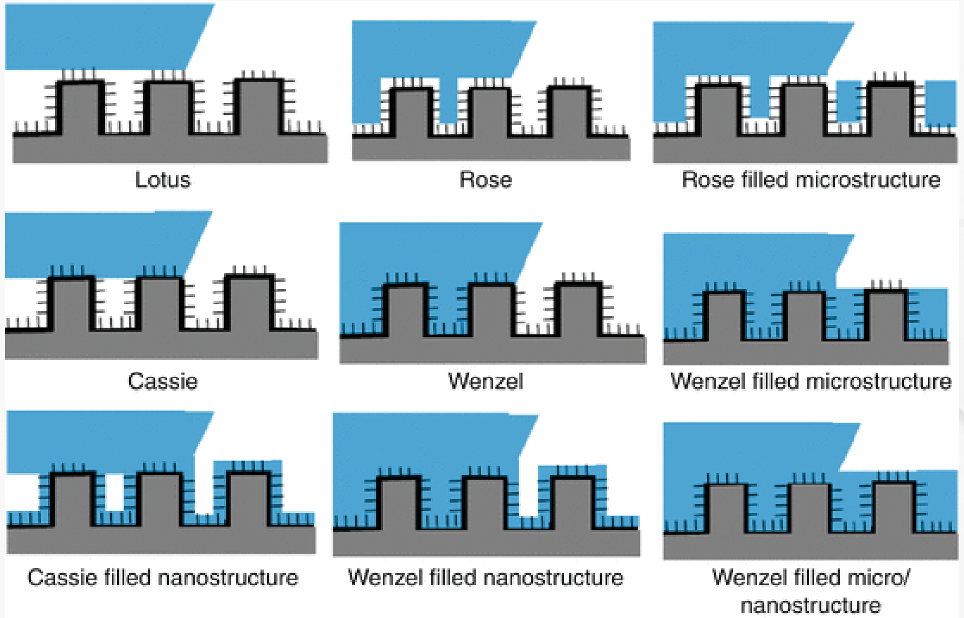


An illustration of the differences of wetting: (a) isotropic (uniform, randomly rough) surface, (b) anisotropic (grooved) surface, (c) real goniometry photos of anisotropic surface.

Different wetting states at different scales lead to different droplet behaviour

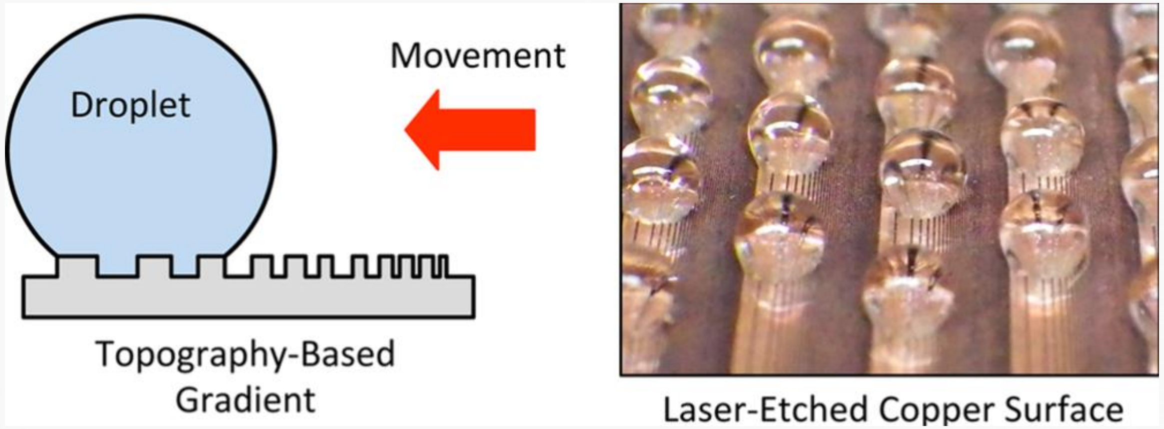
Bhushan B., Nosonovsky M. (2012) Rose Petal Effect

https://doi.org/10.1007/978-90-481-9751-4_157



TOPOGRAPHY GRADIENT MANUFACTURING IDEAS

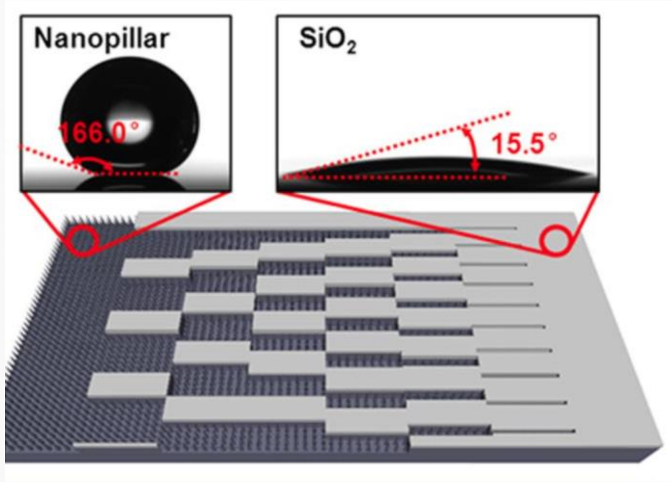
Microgrooves



A. D. Sommers et al., Langmuir, 2013, 29, 12043−12050

- made on copper via laser etching;
- Wenzel state (not superhydrophobic);
- relatively short travel distance;

Stripes

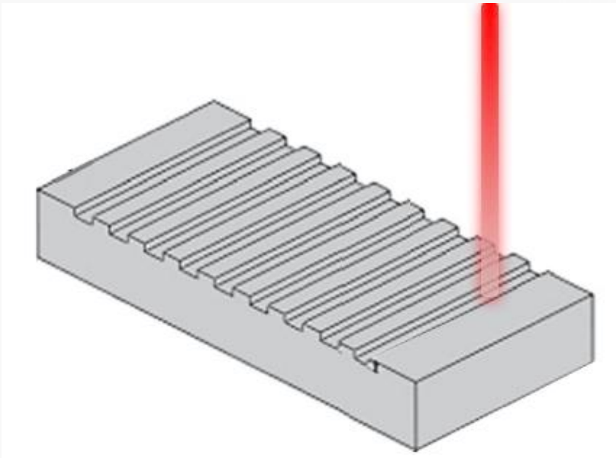


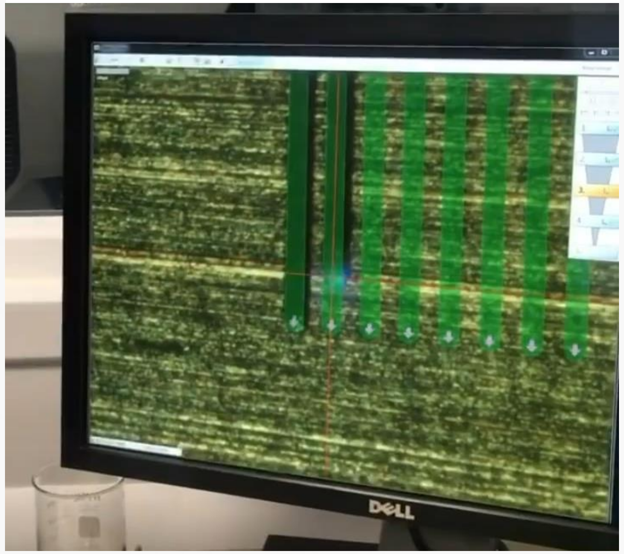
C. Liu et al., Sci Rep, 2017, 7, 7552

- made on silica/SiO_2 via UV-lithography and reactive-ion etching;
- all wetting states along the gradient;
- relatively long travel distance;

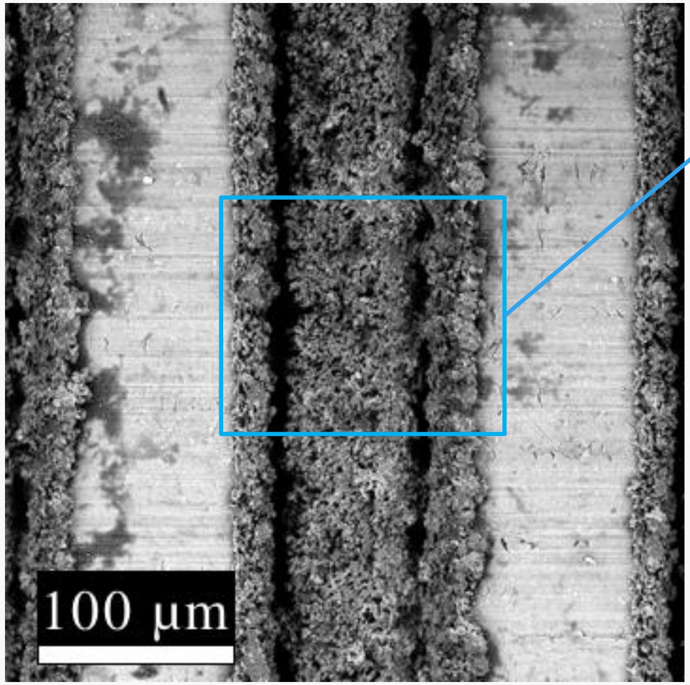
MICROFABRICATION

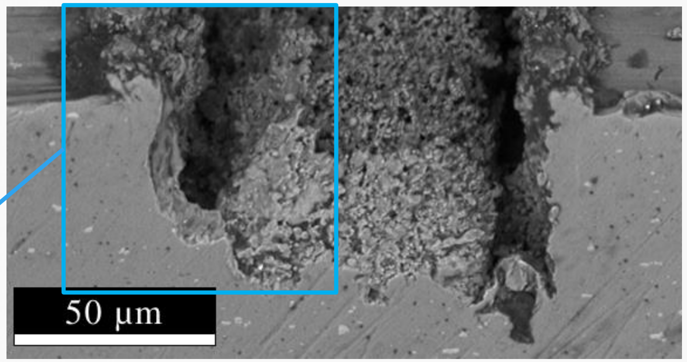
Laser-etching



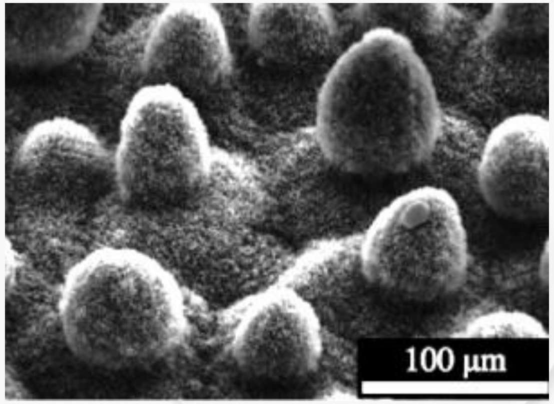


Resultant structure





Similar to lotus!



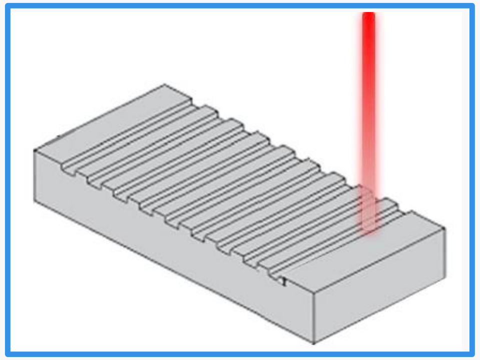
H. Zhang et al., 2012

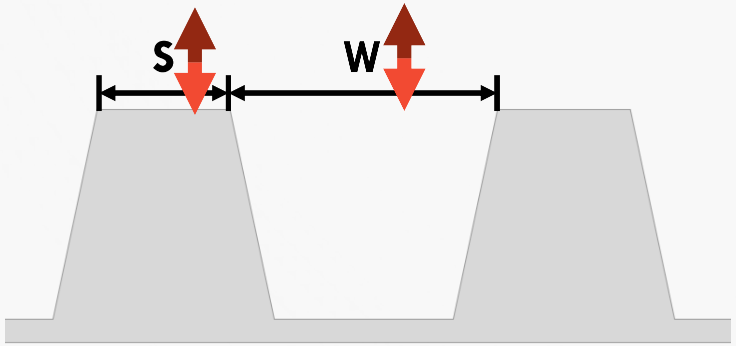
	Microstructure	Nanostructure
Lotus surface	3 – 15 µm	40 – 200 nm
Laser-etching	3 – 20 µm	50 – 250 nm

K. Misiiuk et al., Langmuir, 2022 DOI:10.1021/acs.langmuir.1c02517

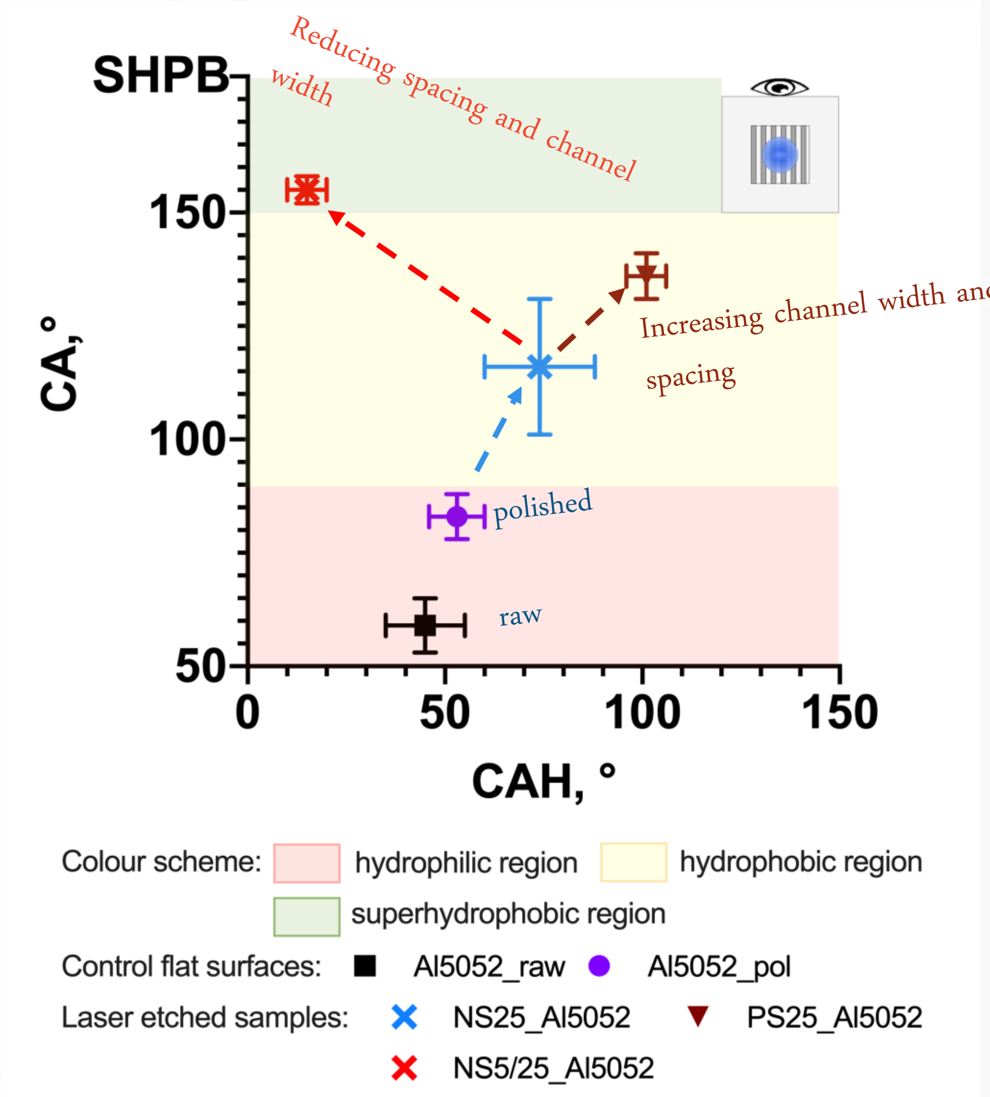
MICROFABRICATION. WETTING BEHAVIOUR

Microfabrication

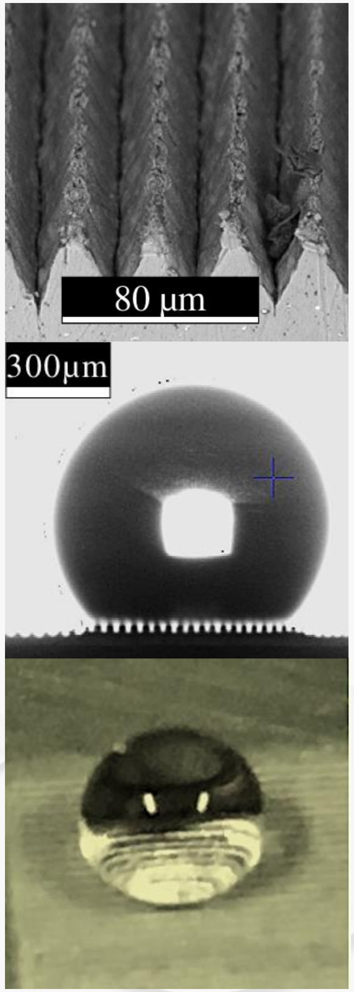




Analysis

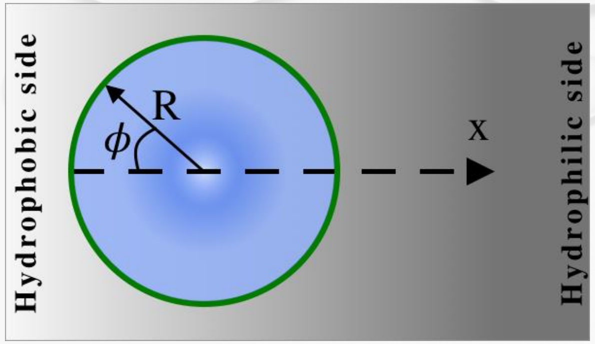


Improvement



K. Misiiuk et al., Langmuir, 2022; DOI:10.1021/acs.langmuir.1c02517

TOPOGRAPHY GRADIENT MODELLING



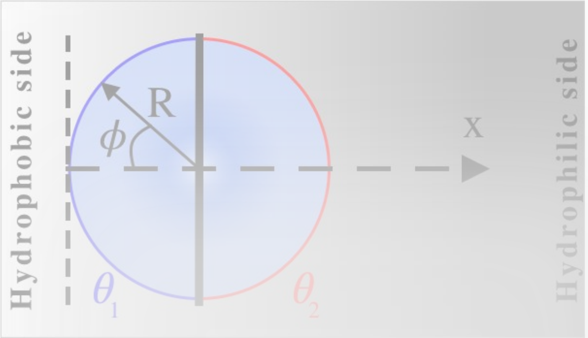
$$F_{acting} = -2\gamma R \int_0^{\pi} \cos\theta \cos\phi \, d\phi$$

$$F_{acting} = F_{driving} + F_{hysteresis}$$

$$F_{driving} = \gamma R^2 \pi \frac{d\cos\theta}{dx}$$

$$F_{hysteresis} = 2\gamma R(\cos\theta_R - \cos\theta_A)$$

S. Daniel, Langmuir, 2002; R. S. Subramanian, Langmuir, 2005;
B. Chandesris, Colloids Surf. A, 2013; Liu et al., Sci. Rep, 2017.



$$F_{acting} = \gamma R \int_0^{\pi/2} [-1 + f(1+\cos\theta_1)] \cos\phi \, d\phi + \gamma R \int_{\pi/2}^{\pi} [-1 + f(1+\cos\theta_2)] \cos\phi \, d\phi$$

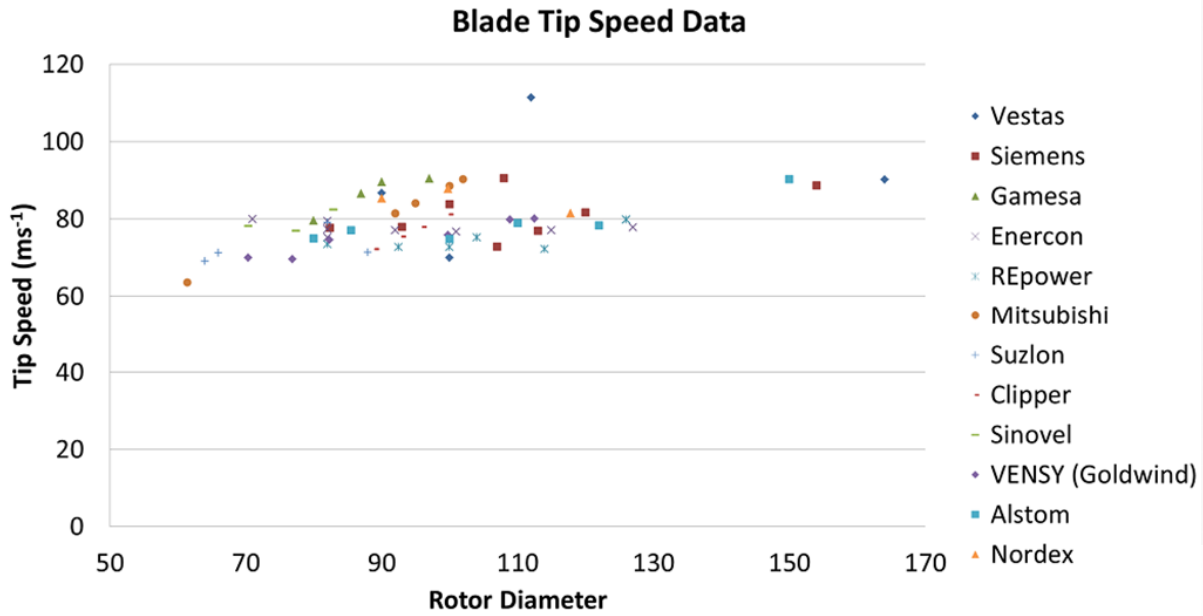
where:

$$f = f_0 + \frac{df}{dx} x = f_0 + \frac{df}{dx} R(1-\cos\phi)$$

K. Misiiuk et al., Langmuir, 2022
DOI:10.1021/acs.langmuir.1c02518

DROP IMPACT FROM THE BLADE POV

UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND



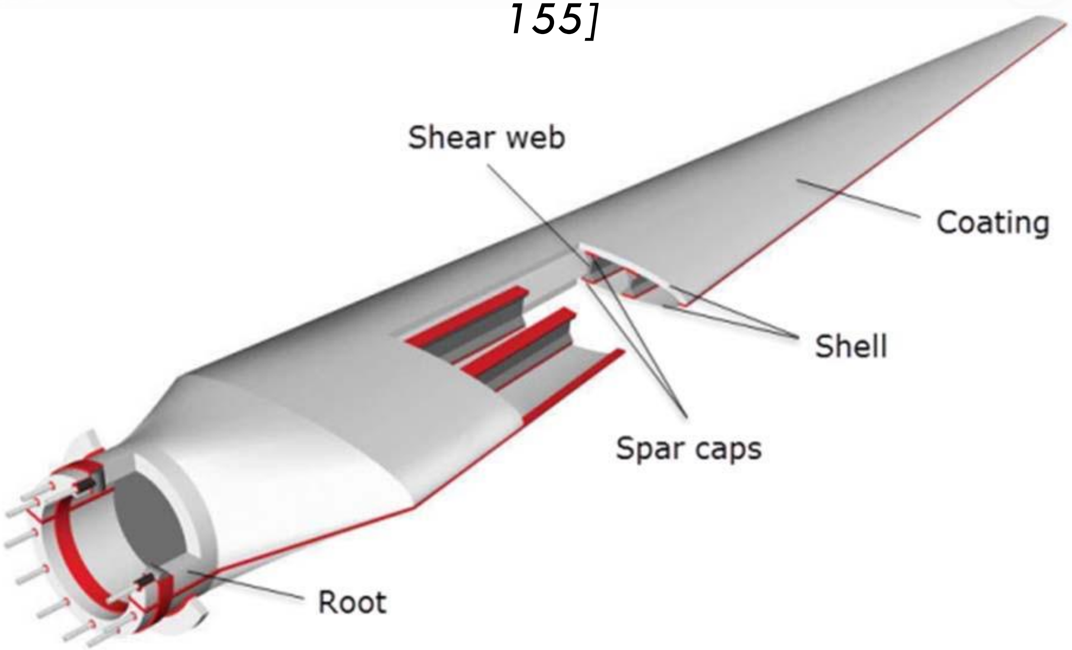
Blade tip speed versus rotor diameter for various utility scale wind turbine blades [*M.H. Keegan et al., J. Phys. D. 46 (2013) 1-20*]

The majority of wind turbine blades use composite materials of thermosetting **polymer** matrix reinforced **with fibers**. The **glass fiber** has been used since the early days of blade manufacturing. **Carbon fibers** are now attracting attention. Other potentially interesting fibers are **aramid, polyethylene,** and **cellulose** *[P. Brøndsted et al., Annu. Rev. Mater. Res. 35 (2005) 505-538].*

It happens in ~2 years

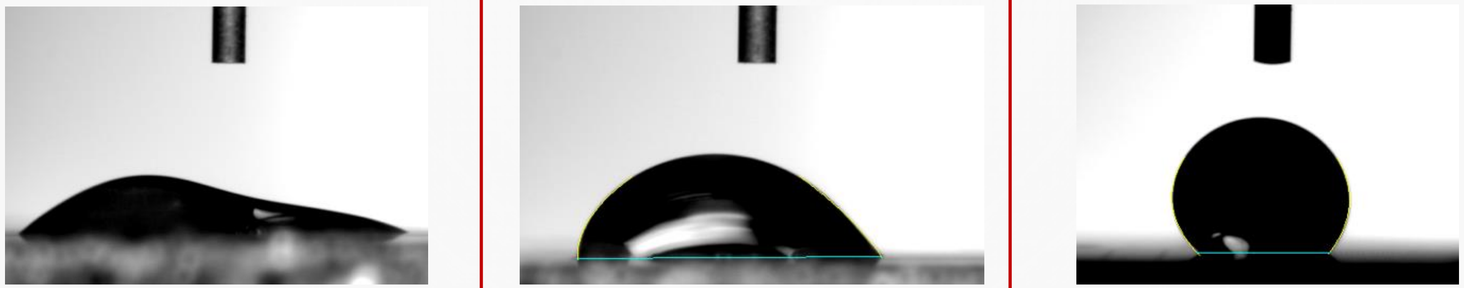
Leading edge erosion of a wind turbine blade
L. Rampel, Wind Systems Magazine (Issue date 24.10.2012) 22-24]

Wind turbine blade structure.
[P. Roth-Johnson et al., Renewable Energy. 71 (2014) 133-155]

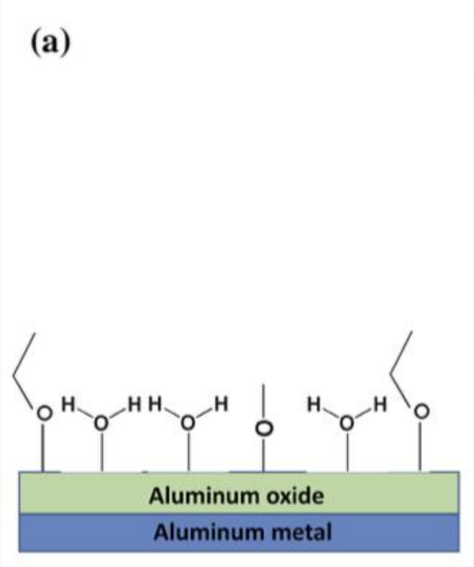


STRUCTURED ALUMINIUM: ACCOMPANYING EFFECT

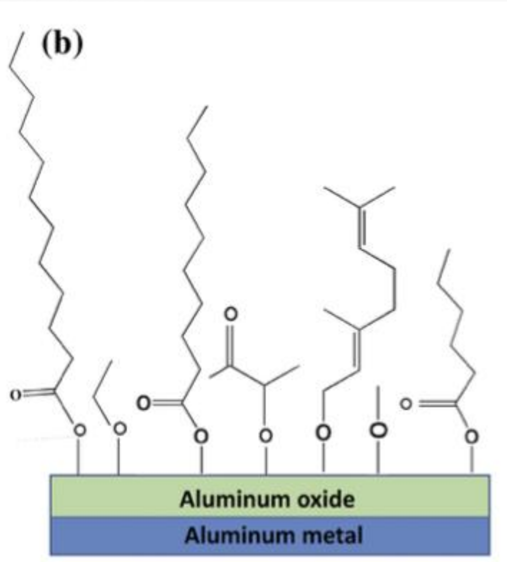
Goniometry photos of a 5 µL droplet at the same spot of a laser-etched sample after various storage time (*K. Misiiuk et al., Langmuir, 2022, DOI:10.1021/acs.langmuir.1c02518*)



minutes → weeks

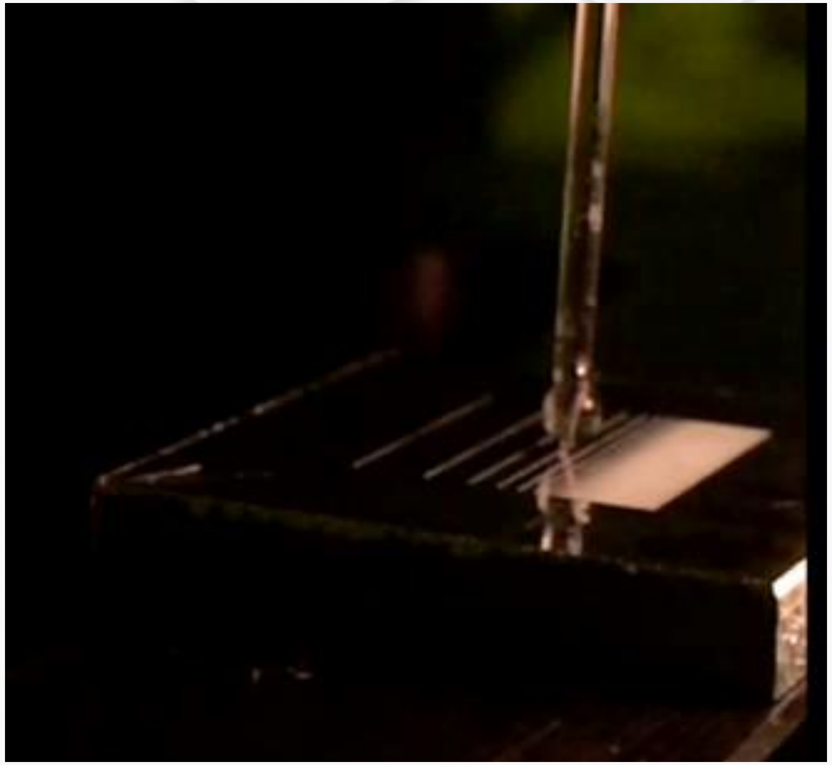


Storage time

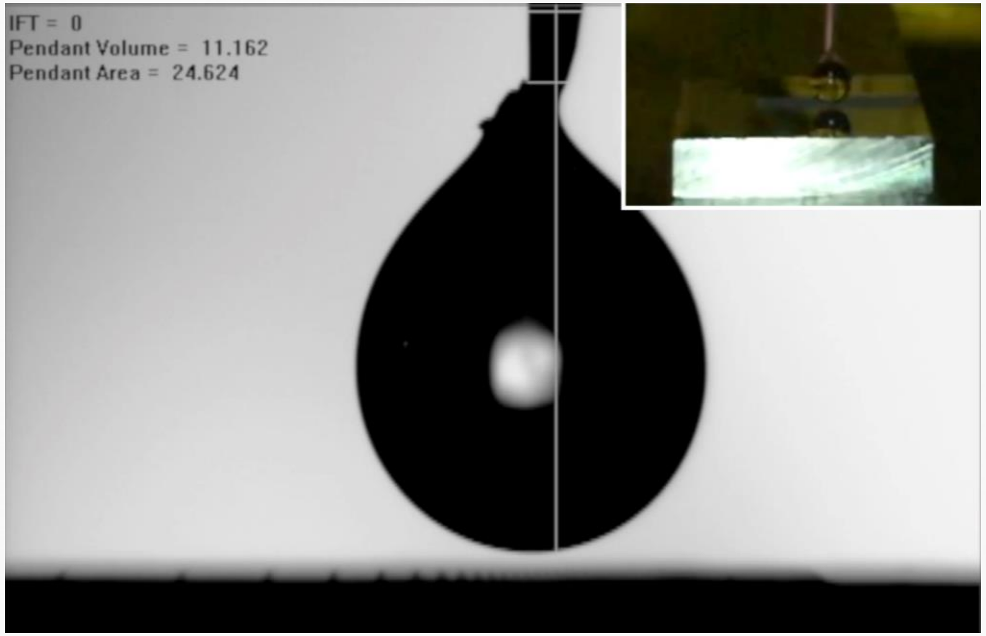


[J. Long et al., J. Colloid Interface Sci., 441, 2015]
[G. Schnell et al., Nanomaterials, 10, 2020].

BIDIRECTIONAL MOVING



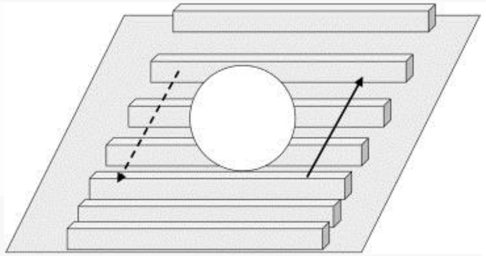
Spontaneous moving (at least directional spreading) in Wenzel state



Spontaneous moving in Cassie-Baxter state (the droplet ends up in Wenzel state)

It's in agreement with Sun et al.

doi:10.1016/j.tsf.2008.01.011.



(< Fig. 2 from the paper). Schematic illustration of a droplet movement on a roughness gradient surface. The moving behaviour depends on the wetting mode. The droplet moves in the direction pointed by the solid arrow when the wettability is governed by Wenzel theory. If the droplet is in Cassie-Baxter state, it moves in the converse direction indicated by the dashed arrow.