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Ilemona S Omeje, Tatiana E Itina. How surface relief affects wettability and cell behavior on ultra-short laser-textured surfaces?. V International Conference on Ultrafast Optical Science, Ultrafastlight, Moscow, Russia, October 2021, Oct 2021, Moscow, on-line, Russia. ujm-03829708

HAL Id: ujm-03829708

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Submitted on 25 Oct 2022

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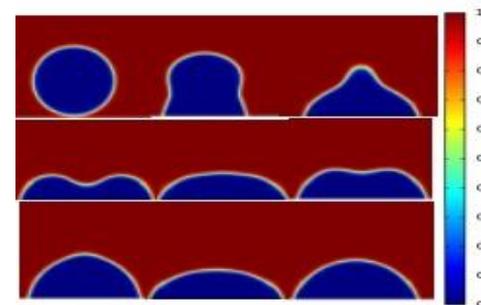


How surface relief affects wettability and cell behavior on ultra-short laser-textured surfaces

Ilemona S. OMEJE and Tatiana E. ITINA,

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* tatiana.itina@univ-st-etienne.fr



Cells on surfaces

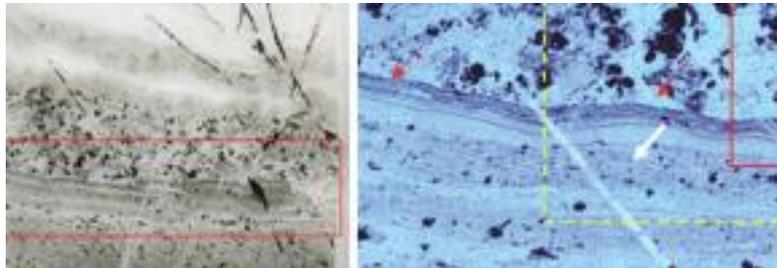
On the origin of life: recent engineer's point of view



There are more and more new evidences that “first cells could have formed at **the surface of porous minerals**” ...

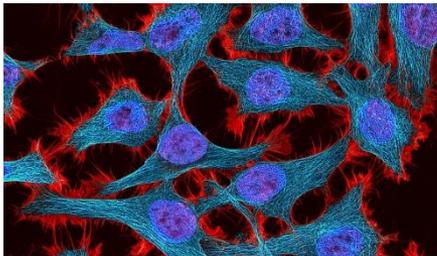
HYDROTHERMAL-SEDIMENTARY ORIGIN OF LIFE

Westall et al ASTROBIOLOGY V 18 (3) 2018

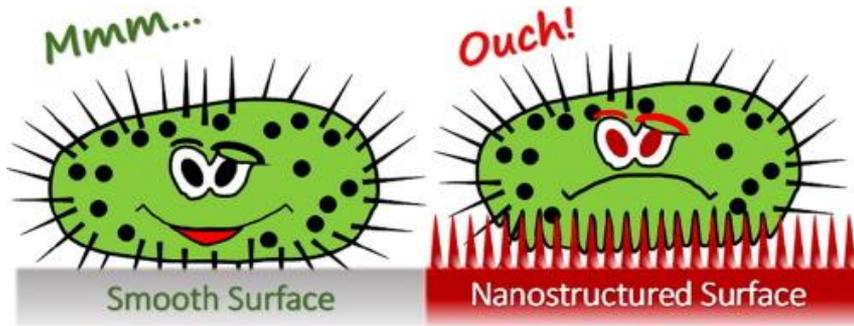


“A primeval metabolism begins in water **at the surface of minerals...**”

These promote the polymerization of some of the elementary building blocks, including RNAs. An RNA-metabolism world develops and leads to the replication of these RNAs, eventually forming an RNA-genome world which then uses RNA molecules as information templates (primitive genes) rather than as direct substrates for metabolism.



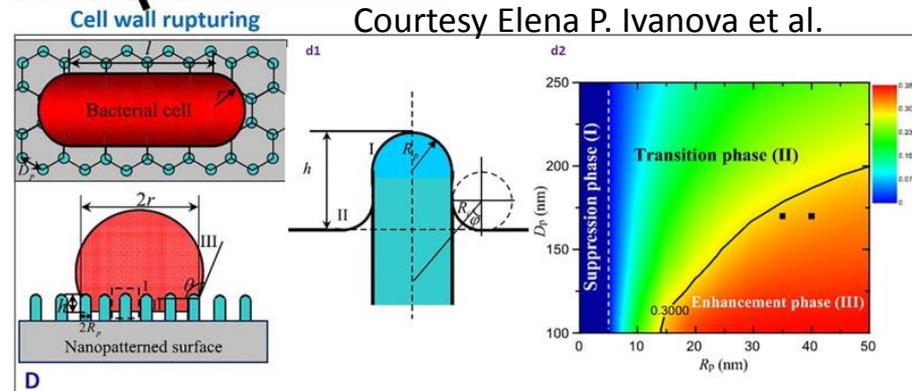
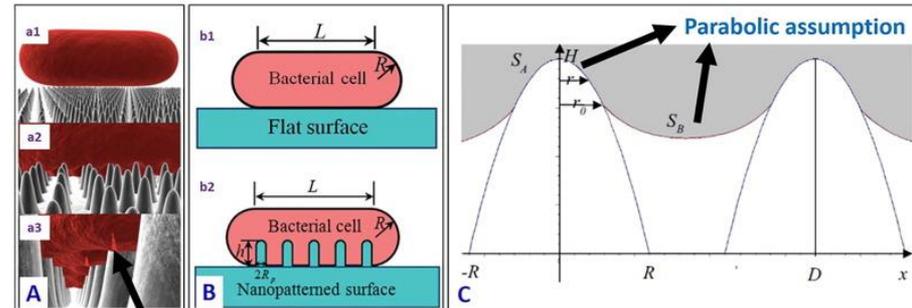
Cells on surfaces



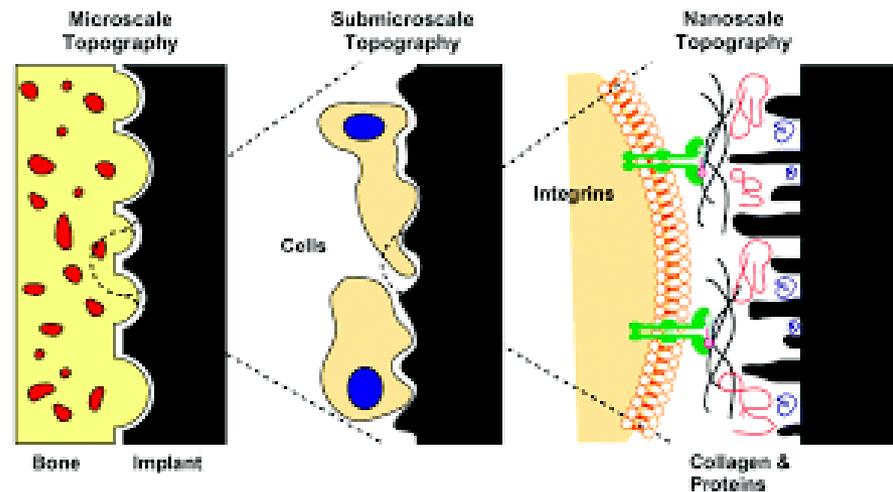
Between protection and defence ?

Numerous factors can be important

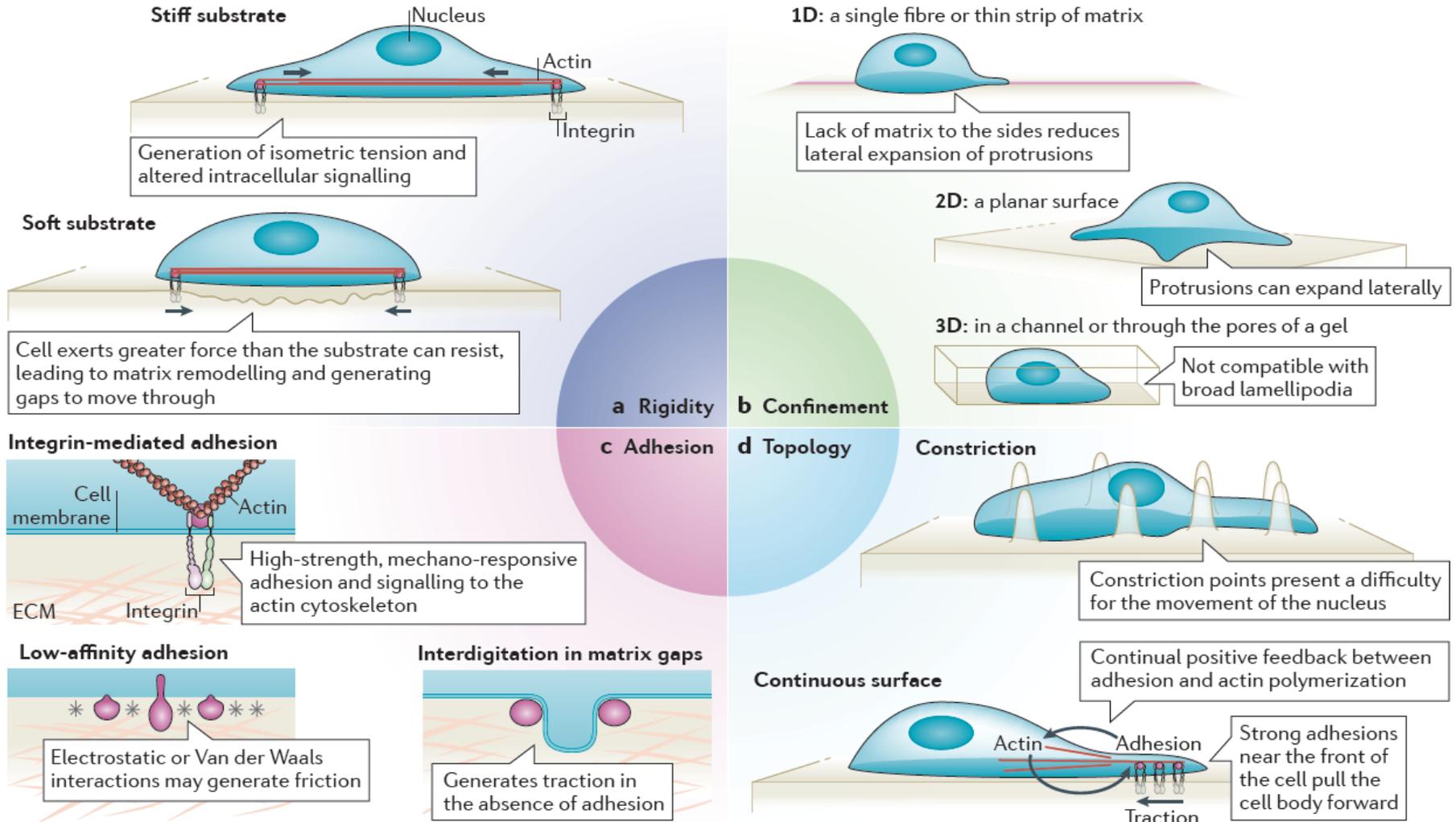
- cell types, size, properties
- surface material
- background gas or liquid
- surface topography
- topology
- Etc...



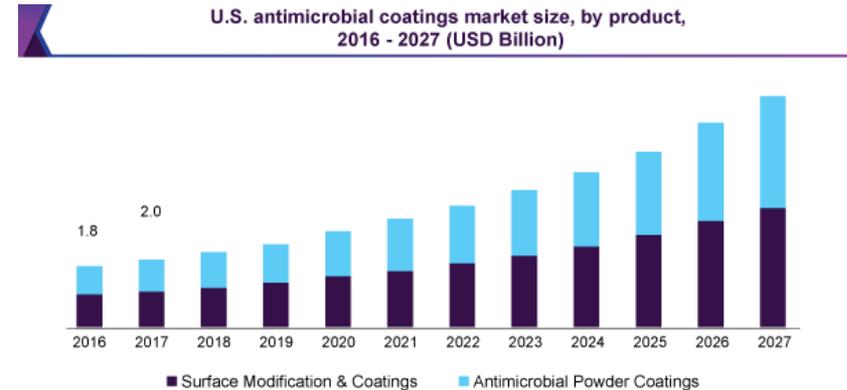
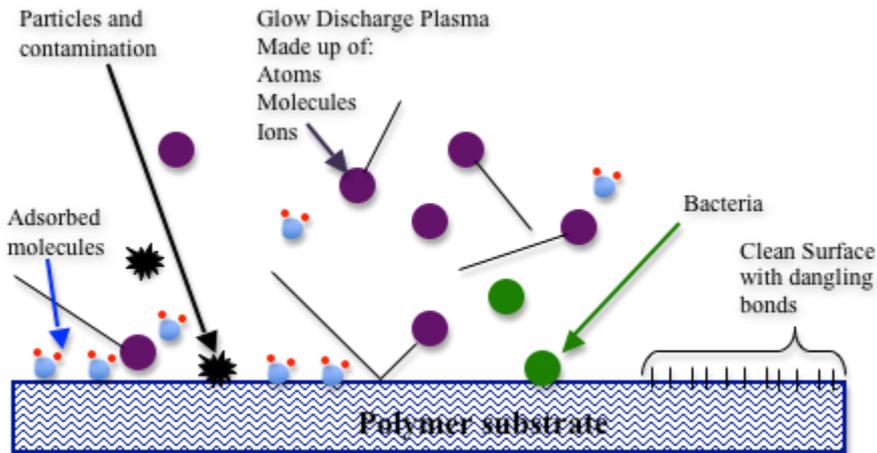
Courtesy Elena P. Ivanova et al.



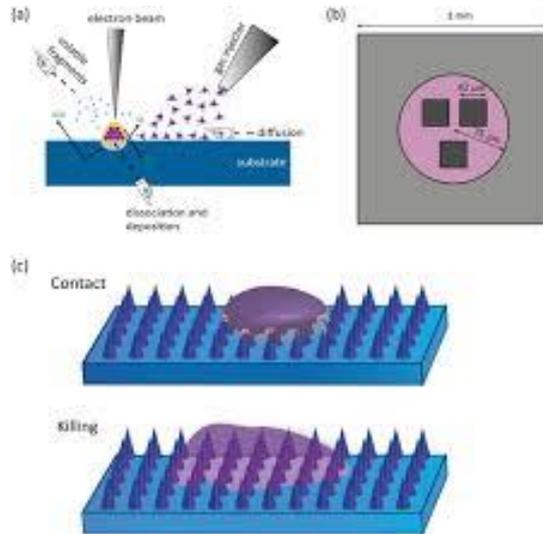
Cells : physical influences



Antimicrobial coatings vs surface texturing

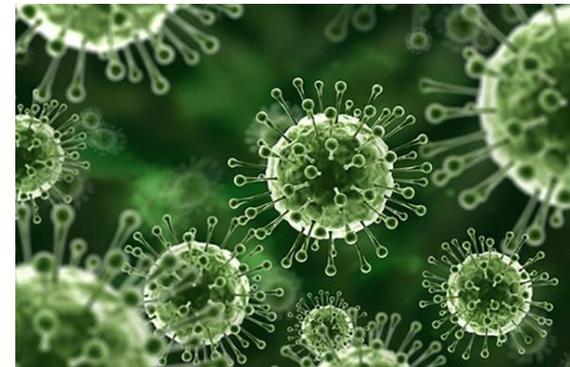


Bio-inspired surface structures



Microbes include:

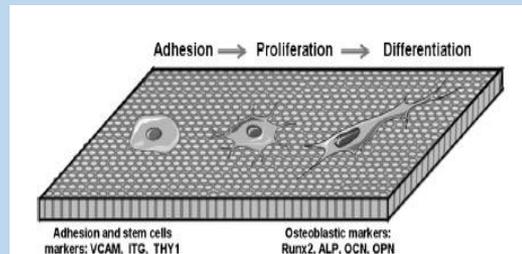
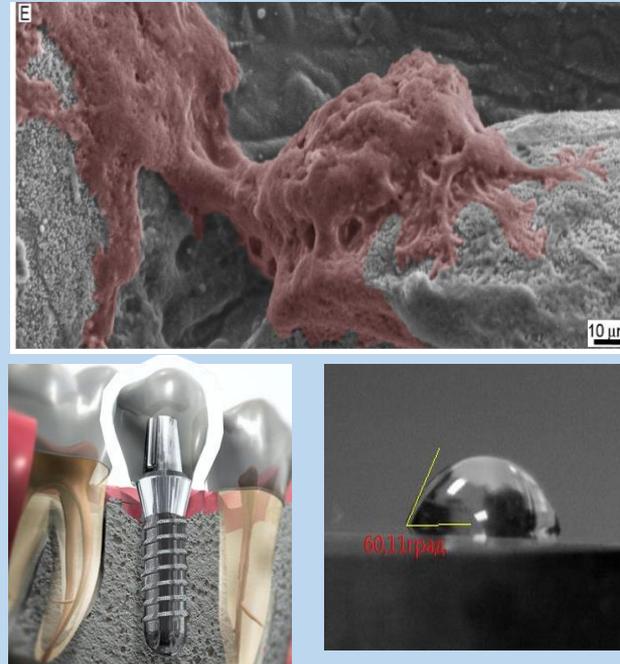
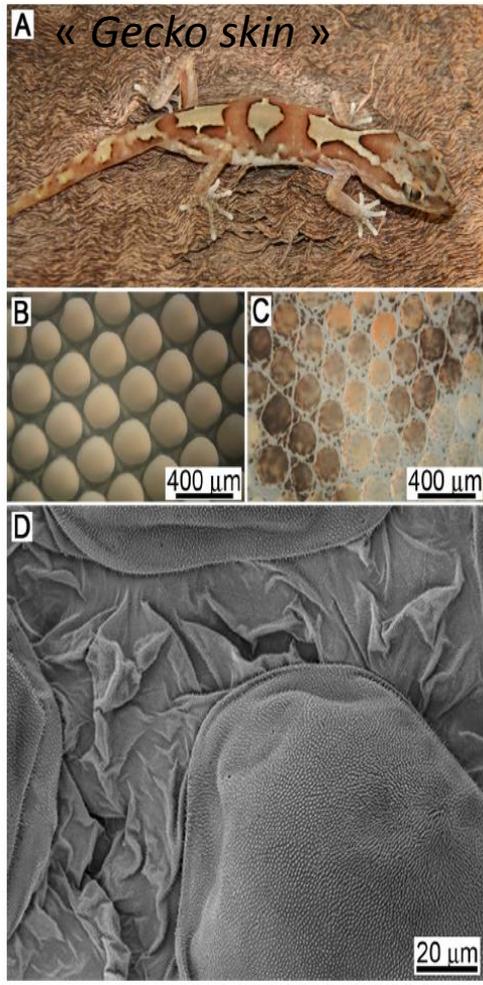
- fungi
- bacteria
- algae
- virus



Nature Helps: Toward Bioinspired Bactericidal Nanopatterns

Mahya Ganjian et al, Advanced Materials, 06 June 2019

Role of textured surfaces



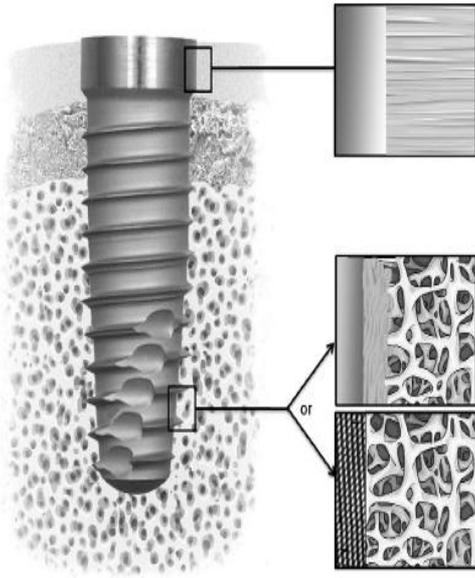
- Analogy with **the gecko skin** - wetting control and adhesion properties
- The texturing of surfaces is **a key step toward better bio-integration** of prostheses, implants, scaffolds
- **Hydrophilic** surface promotes the interaction of the surface with cellular elements, which is of particular importance in the **early stages of osseointegration**

G. S. Watson et al. « A gecko skin micro/nanostructure ... »
Acta Biomaterialia 21 (2015), 109-122

S. Lavenus et al., *Impact of nanotechnology on dental implants.*

Yu. Karlagina et al.
 ITMO Univ.

Dental implants: different parts - different treatment

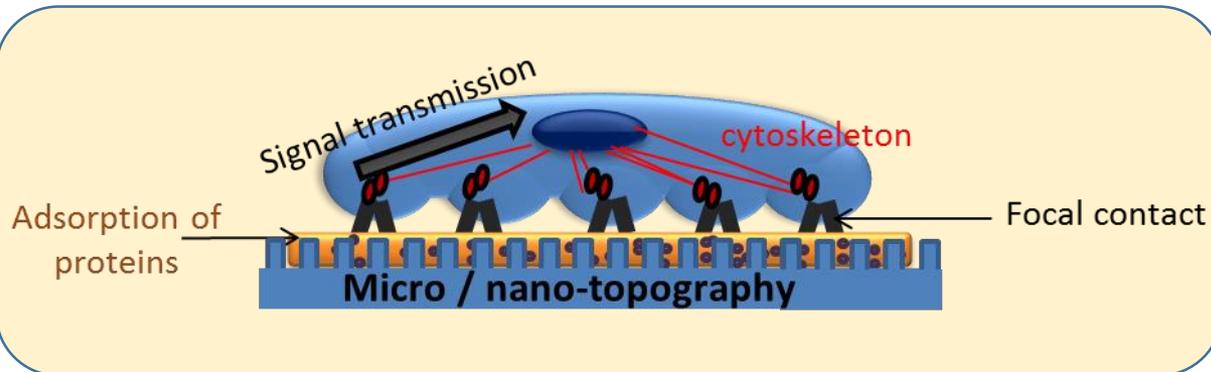


In contact with the gingiva – a texture allowing the development of gingival fibroblasts and limiting the adhesion of bacteria.

In contact with the bone tissue - should promote the differentiation and mineralization of bone cells to optimize osseointegration.

Here, we will concentrate on osseointegration

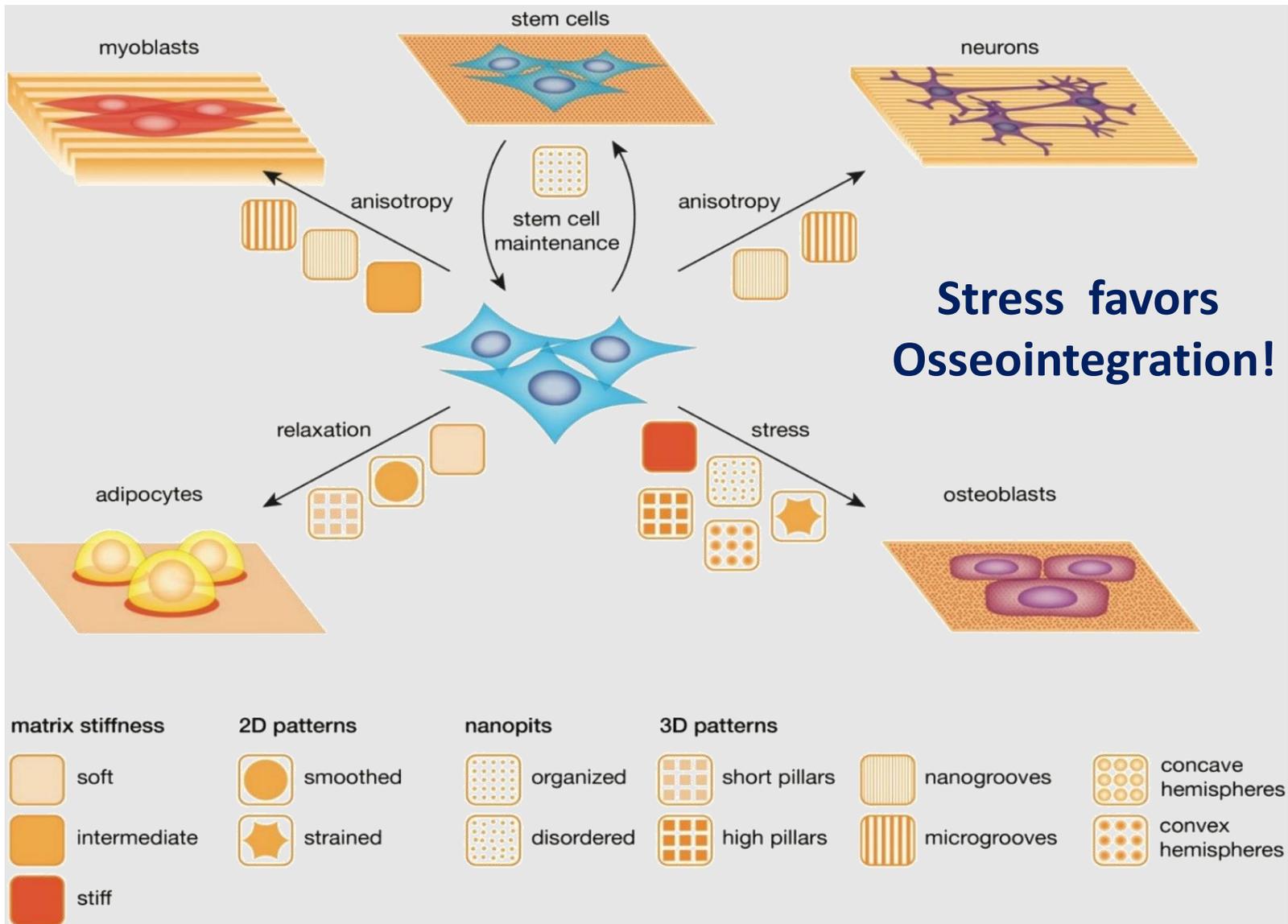
Stem cells on textured surfaces



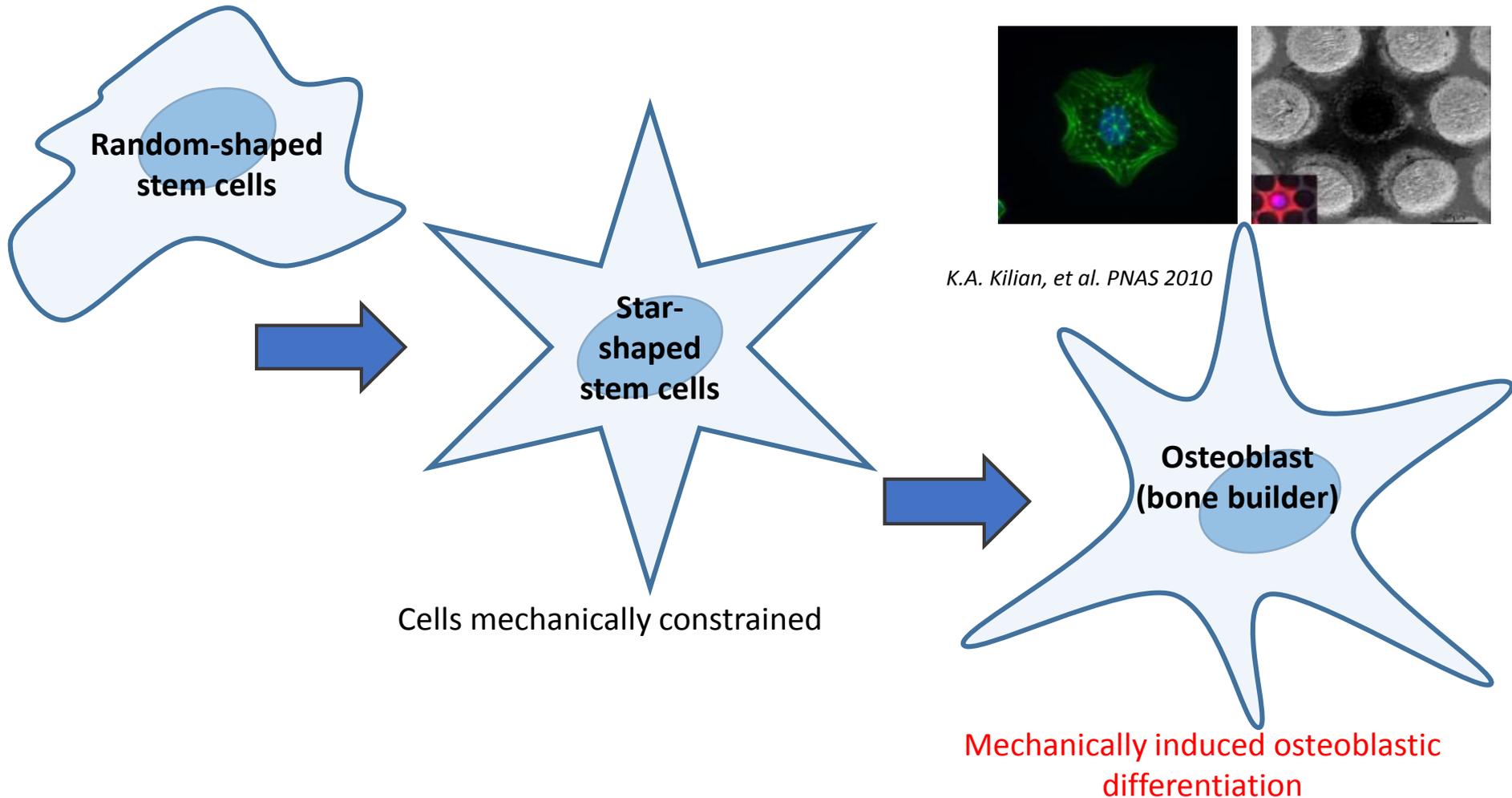
- Mechanotransduction
- Growth
- Osteoblast differentiation

Surface Modifications for Osteoblastic Differentiation

K.A. Kilian et al., PNAS 2010

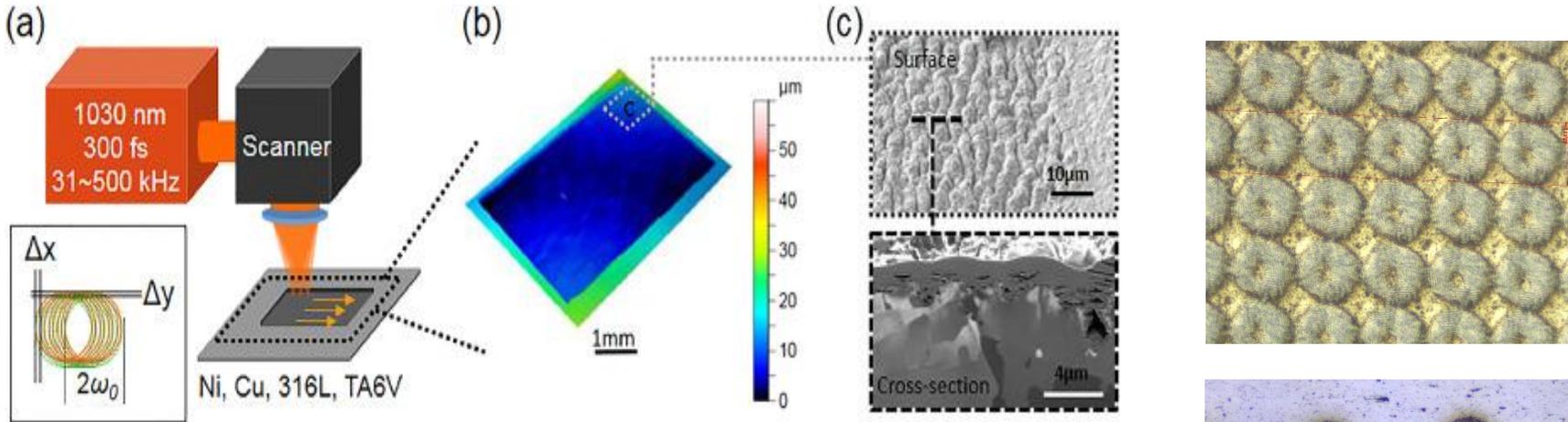


Ways to get osteoblast differentiation

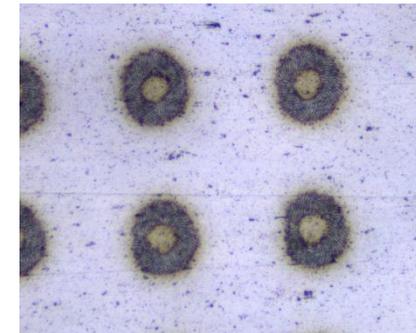
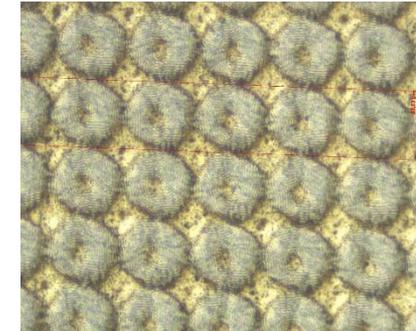
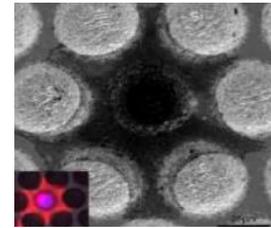


We will try to guide cell to get a « star-like » extended shape to favor osseointegration.

Advantages of Femtosecond Lasers



- Can easily produce surface structures
- Can vary the size and the shape of the structures by reducing the thermal effect
- Favors a better control and a better quality
- Can minimize contamination and debris
- Can alternate hydrophobic and hydrophilic properties



It remains to define the best surface relief, the optimum laser parameters.

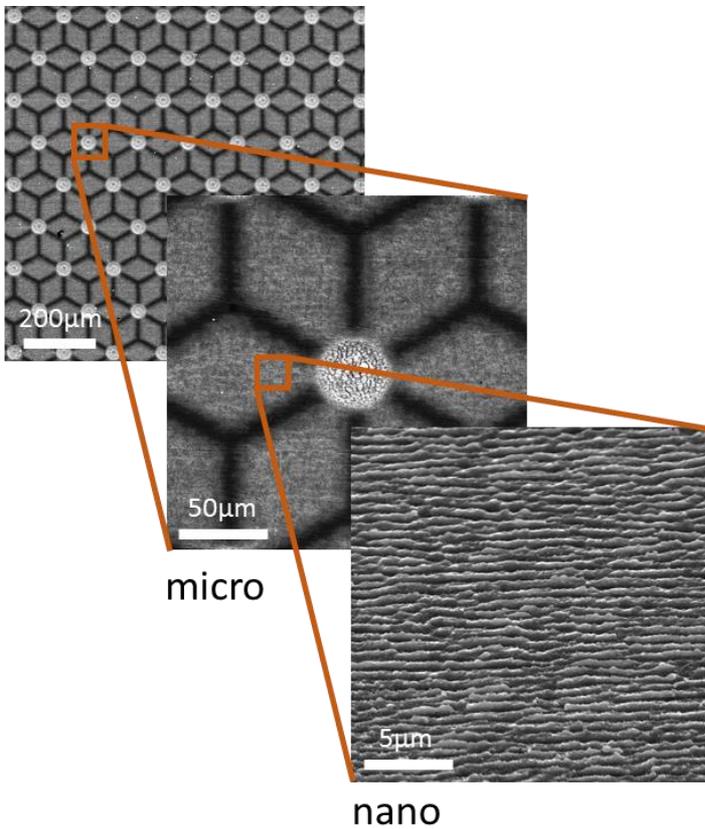
For this, a better understanding of wetting on textured surfaces is required.



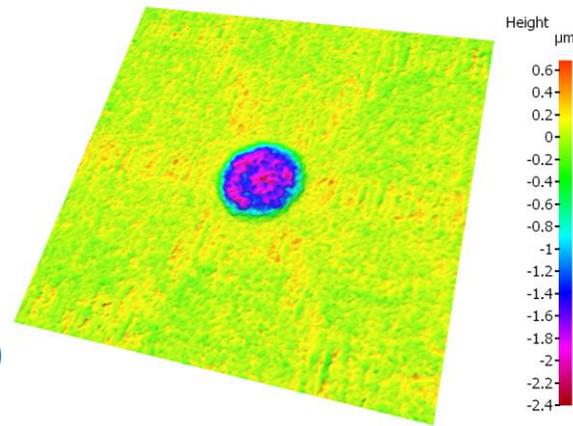
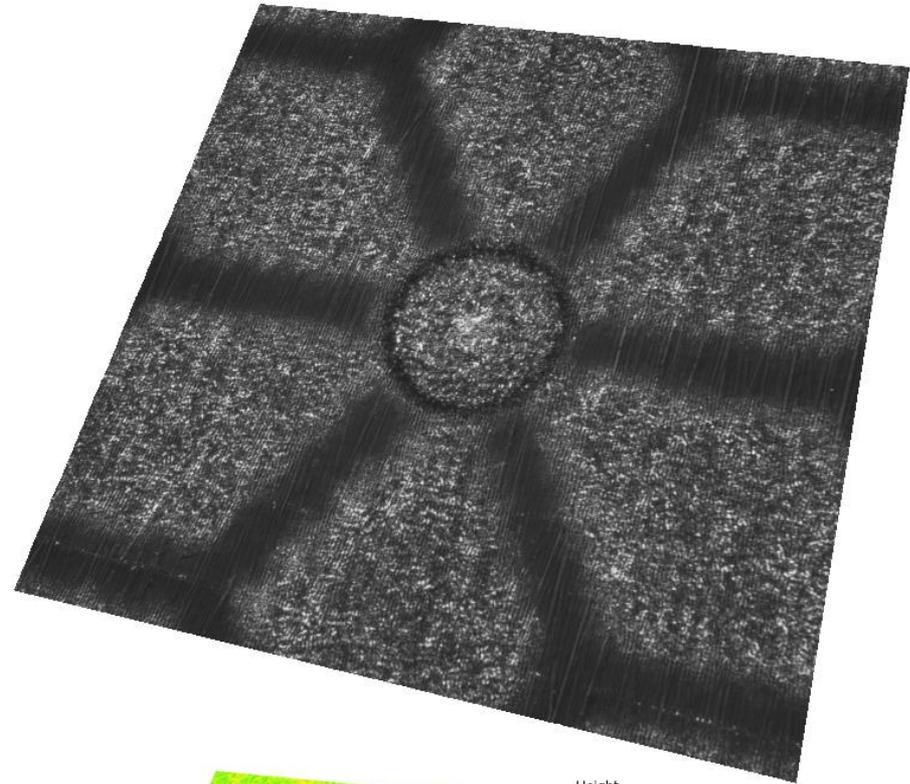
X. Sedao et al. Optics and Lasers in Engineering
116, May 2019, Pages 68-74

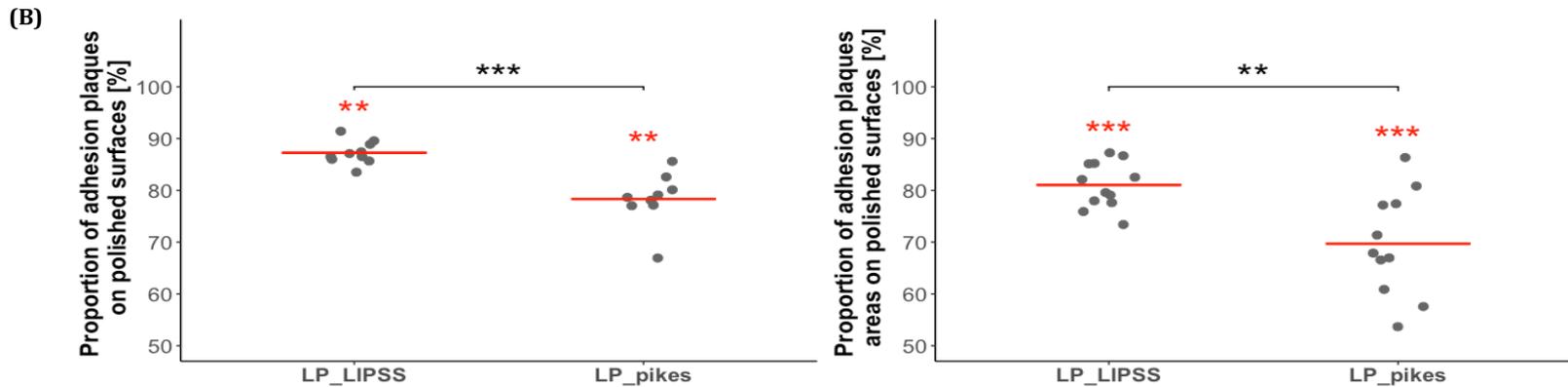
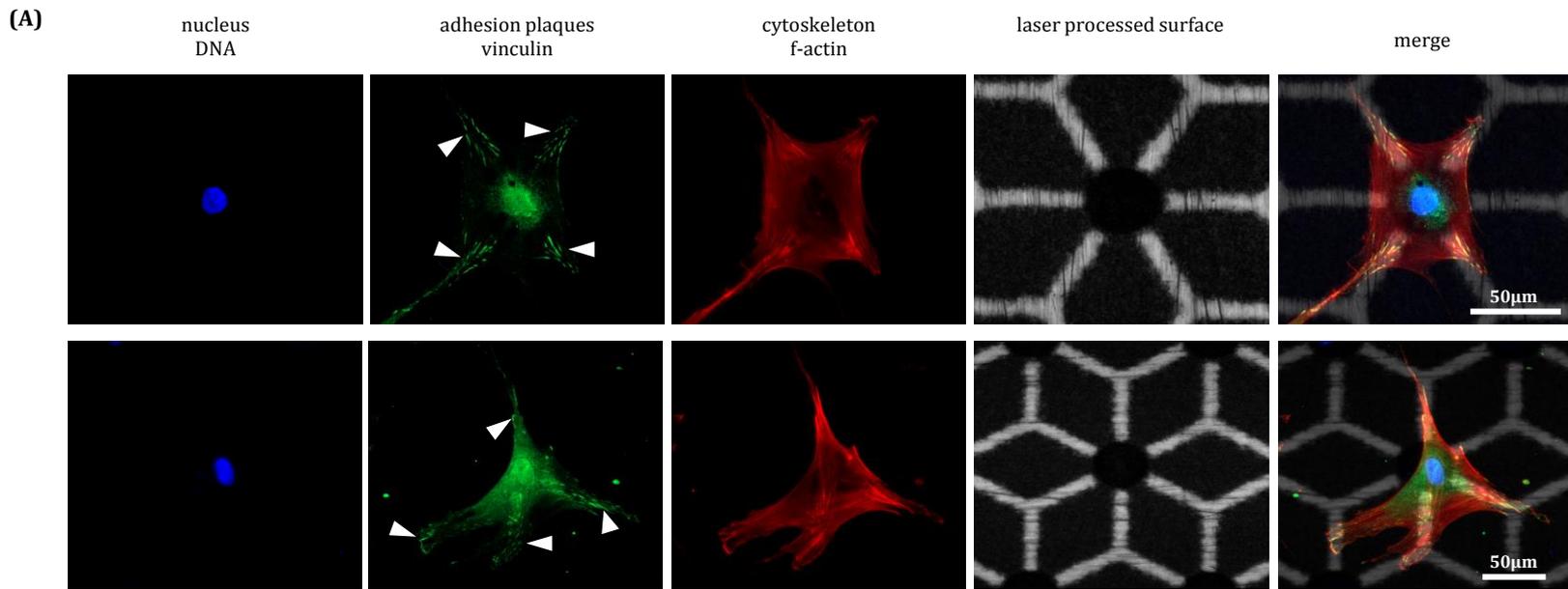
Multi-scale Laser Patterning

Hierarchical surface relief



Knowledge-Based





(A) hMSCs exhibits preferential focal adhesion location on polished areas (white arrows), nucleus inside a pit, and cytoskeleton star-like shaped. DNA is shown in blue, vinculin in green, actin in red.

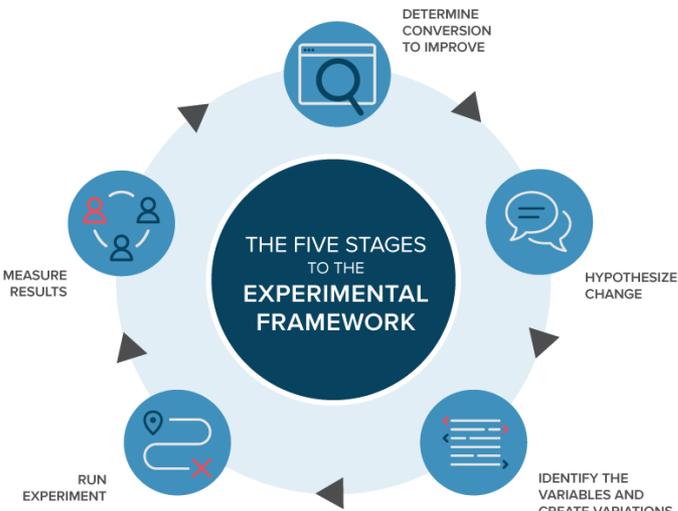
(B) Ratio of **adhesion plaques on polished regions** compared to **adhesion plaques on laser-nanostructured** ones was obtained either by counting the number of adhesion plaques per cell (left panel) or by measuring the areas of the adhesion plaques per cell (right panel). **Data shows a significant differences between *LP_LIPSS* and *LP_spikes* concerning the number and the area of adhesion plaques per cell. Red lines denote mean values.**

How Modeling Can Help?



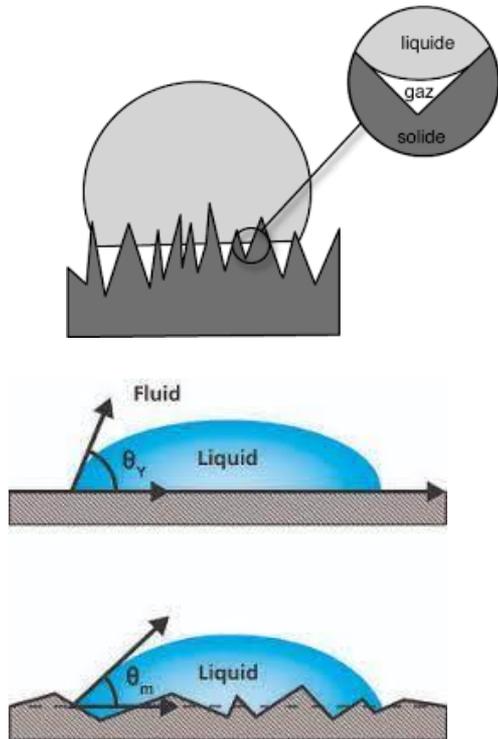
Main objectives of the modeling

- to reduce the number of tests
- to optimize laser treatment



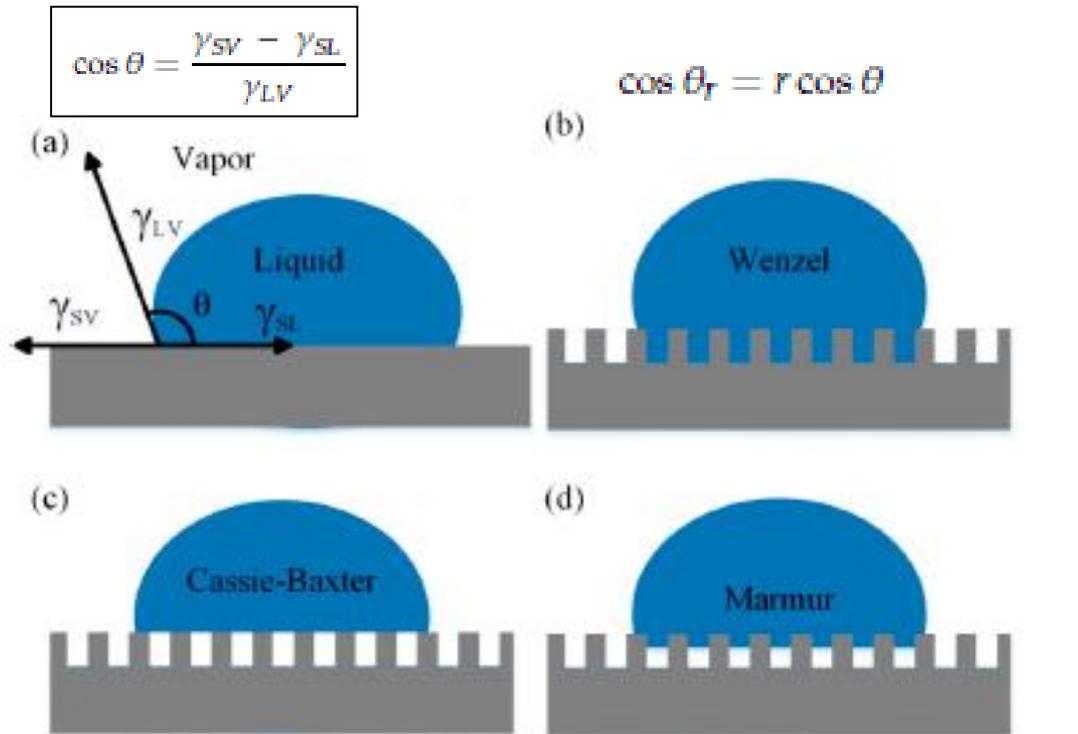
- To explain/predict the connections of cell/bacteria behavior with surface materials and relief
- To explain/predict the best materials and structure parameters for the required wettability
- To determine the best/required laser parameters

Effects of surfaces roughness on wettability



Wettability changes with surface relief, with surface/liquid/gas compositions, with droplet size and...

Wettability changes with ...time!

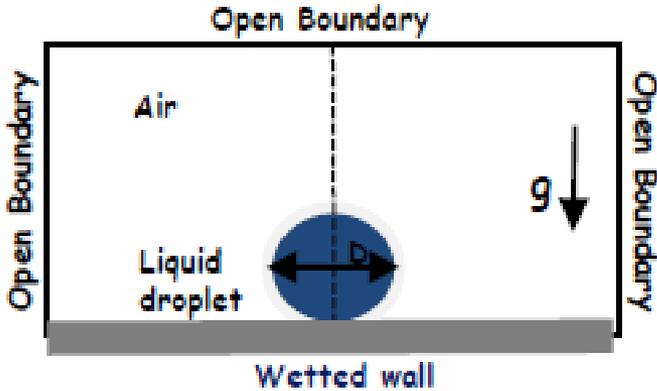


$$\cos \theta_r = f_{SL} \cos \theta_1 + f_{LA} \cos \theta_2$$

$$\cos \theta_r = r f_{SL} \cos \theta + f_{SL} - 1$$

The theories of wetting for a textured surface are often based on Cassi-Baxter and Wenzel models that are over 50 years old and are oversimplified.

Computational Fluid-Dynamics CFD Model



Level Set Method (Interface tracking)

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \gamma \nabla (\epsilon_{ls} \nabla \phi - \phi(1 - \phi) \frac{\nabla \phi}{|\nabla \phi|})$$

$$\rho = \rho_1 + (\rho_2 - \rho_1)\phi$$

$$\mu = \mu_1 + (\mu_2 - \mu_1)\phi$$

Kisler Model: Dynamic contact angle (θ_d)

$$\theta_d = f_H [Ca + f_H^{-1}(\theta_e)]$$

$$f_H = \arccos \left\{ 1 - 2 \tanh \left[5.16 \left(\frac{x}{1 + 1.31x^{0.99}} \right)^{0.706} \right] \right\}$$

Navier-Stokes (Fluid Flow)

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-P\mathbf{I} + \mathbf{K}] + \mathbf{F} + \rho \mathbf{g}$$

$$\rho \nabla \cdot \mathbf{u} = 0$$

$$\mathbf{K} = \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$$

$$F_{st} = \sigma \delta \kappa \mathbf{n}_{int} + \delta \nabla_s \sigma$$

$Ca = \frac{\mu U_{cl}}{\sigma}$ is Capillary number representing the relative effect of viscous drag forces versus surface tension forces acting across interface

U_{cl} is contact-line velocity

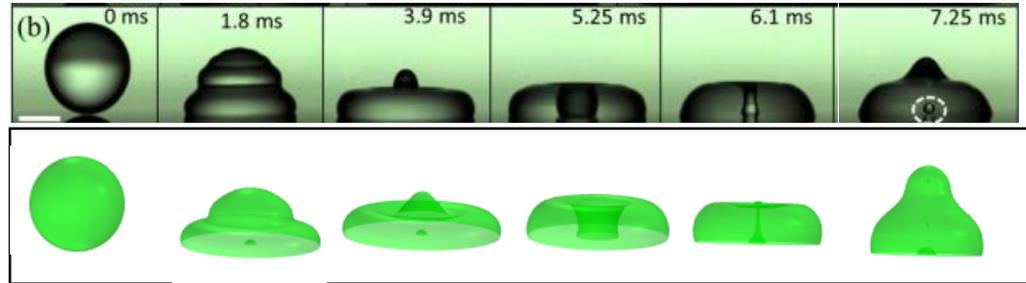
S.F Kisler, Hydrodynamics of wetting, JC Berg (Ed.) Wettability, New York, 1993.

Calculation Results: Model Validation

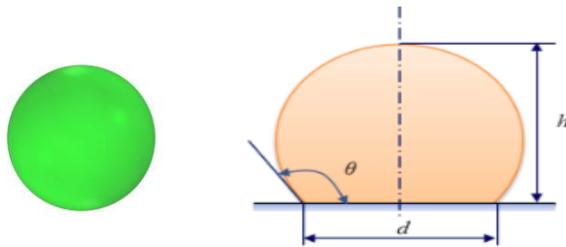
Simulation of water droplet falling on glass

Properties of Water and Air

Parameters	Value
Density of water	997 Kg/m ³
Dyn. visc. of water	0.9 mPa.s
Density of air	1.204 Kg/m ³
Dyn. visc. of air	1.814*10e-5
Surf. liq.-air	0.0718



Shiji et al (2018)

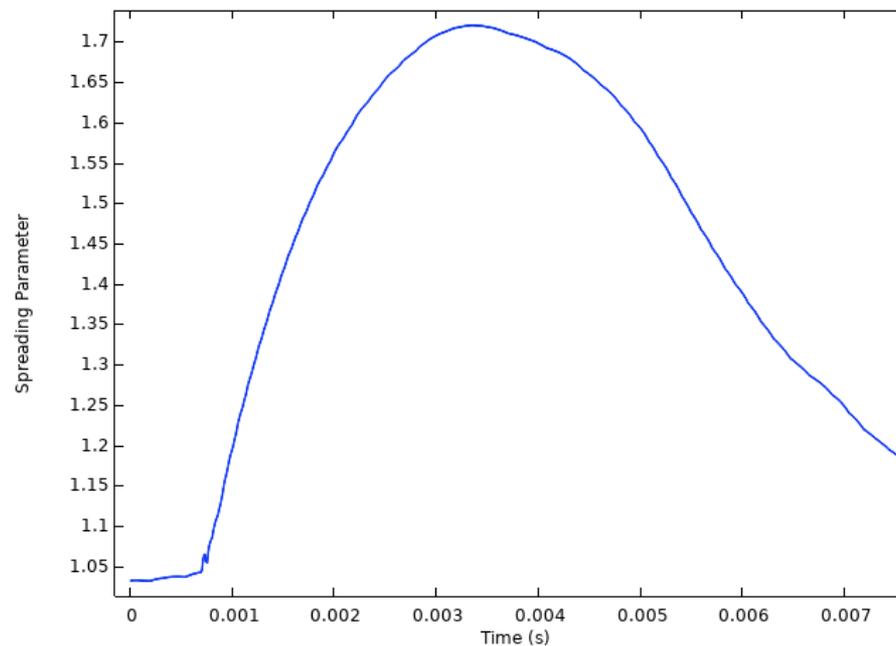


Diameter of droplet = 2 mm

Impact velocity = 0.56 m/s

Equili. Contact Angle = 106

Spreading Parameter (d_s/d_0)

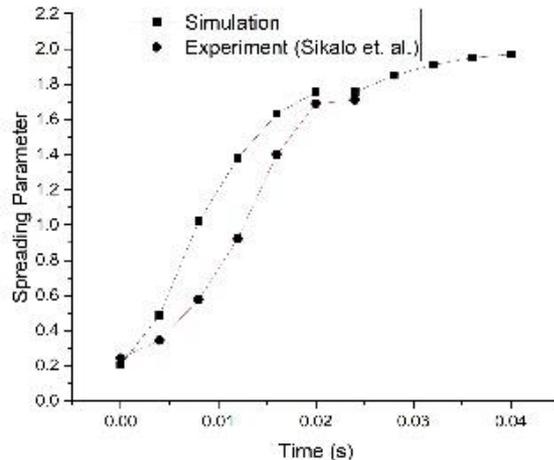


Shiji et al (2018), Impact of viscous on different wettability, Journal Colloid & Interface Science (Experiment)

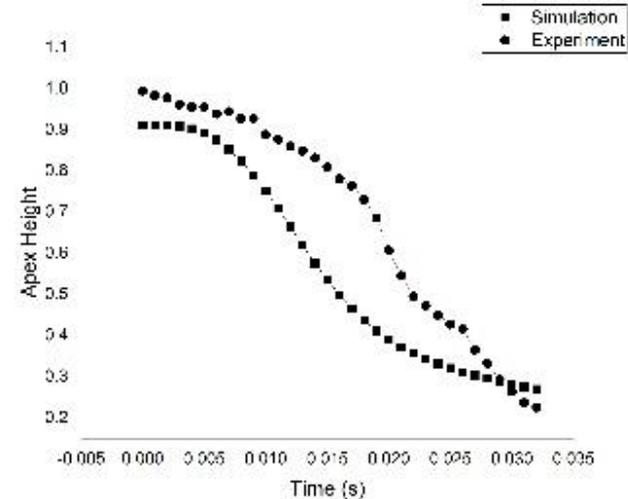
CFD Results: Droplet Dynamics

Glycerol Droplet Dynamics on wax: Experiment vs Simulation

ds/dt

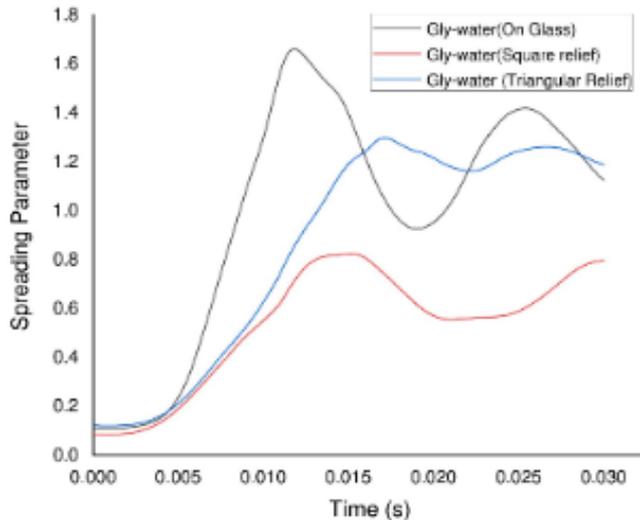


dh/dt



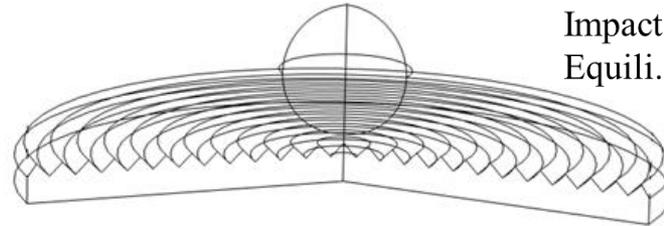
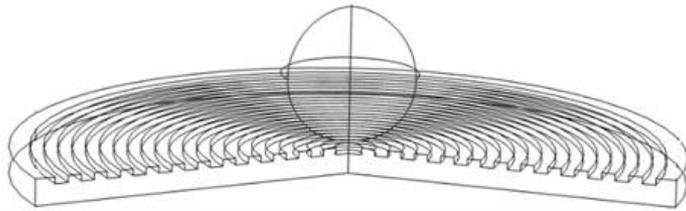
Glycerol-Water Droplet dynamics on different textured surfaces

ds/dt



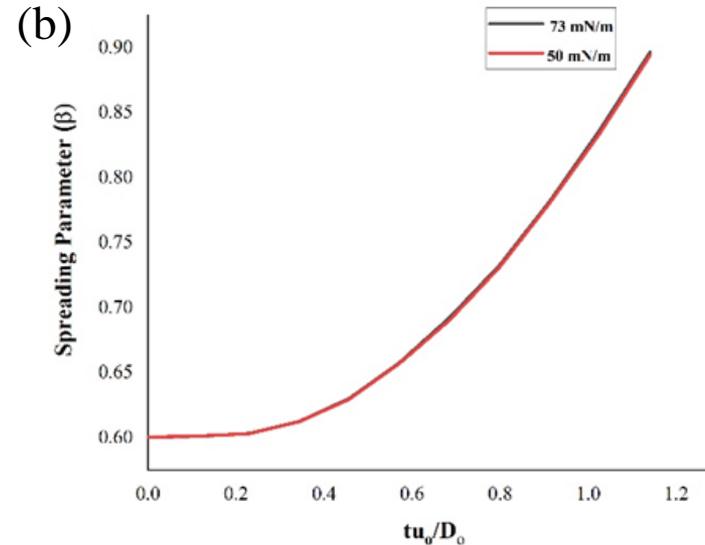
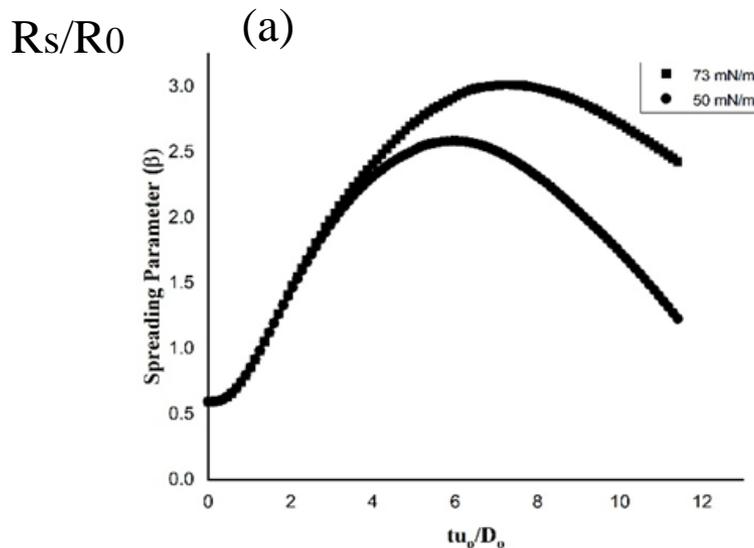
- Simulation results obtained for 2.45mm glycerin droplet on wax at a contact of 15° is compared with the experiments.
- The initial spreading process for the droplet is due to the impact pressure and inertia.
- The dynamics of the droplet on the textured surfaces is different. There is a great impingement of the liquid upon impact. This effect is due to the air pressure within the relief and the roughness of the surface. Oscillations are then observed.

CFD Results: Effects of surface tension on plain and textured surfaces



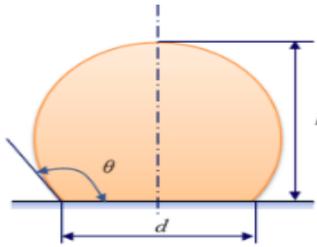
Diameter of droplet = 2 mm
Impact velocity = 0.56 m/s
Equili. Contact Angle = 106

Liquid droplet falls on the periodic rectangular and triangular relief



Spreading parameter on a plain (a) and on a triangular (b) Ti-6Al-4V surfaces at different surface tension.

CFD results: role of the textured surface



$$\text{Spreading factor} = \frac{d}{D_0}$$

$$\text{Apex height} = \frac{h}{D_0}$$

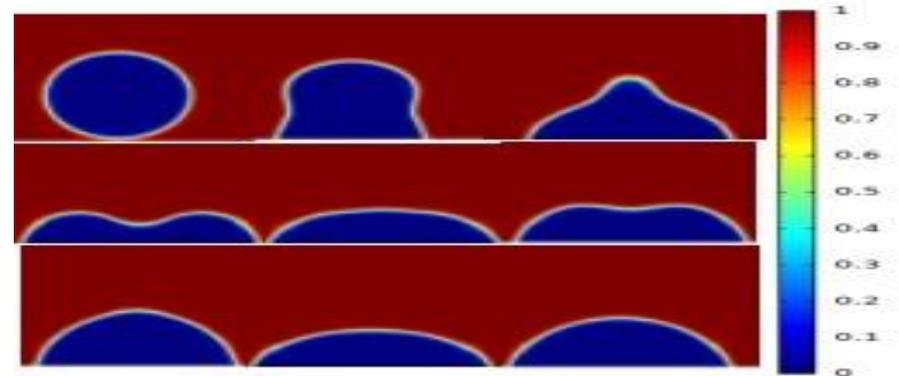
d = diameter of droplet

D_0 = initial diameter

h = apex height of droplet

diameter is 2mm
 the static contact angle (θ_e) is 76°
 at impact velocity of 0.8 m/s

Glycerol-water droplet on glass

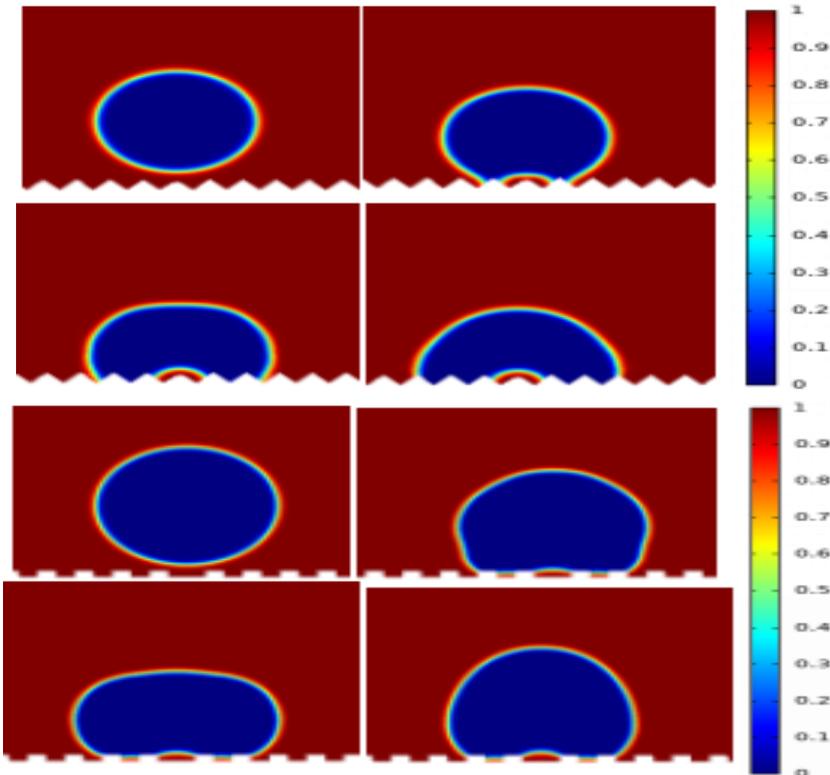


Glycerol-water droplet on triangular relief surface

Glycerol-water droplet on square relief surface

Parameters from:

Shiji L. et. al., Impact of viscous droplets on different wettable surfaces..., Journal of Colloid and Interface Science 516, 15 (2018), pp. 86-97.



Summary

- **Femtosecond lasers** allow us the formation of complex surface reliefs.
- A connection between cell behavior and surface wettability has been established.
- Advanced laser processing solutions are promising for implants surface functionalization.
- **Surface relief, droplet size and impact velocity** play a role in wettability.
- **Spreading parameters such inertial, viscous, capillary and contact-line forces** strongly affect the dynamic contact angle and wetting.

**THANK YOU VERY MUCH FOR
YOUR KIND ATTENTION!**