Three-level multi-scale modeling of electrical contacts

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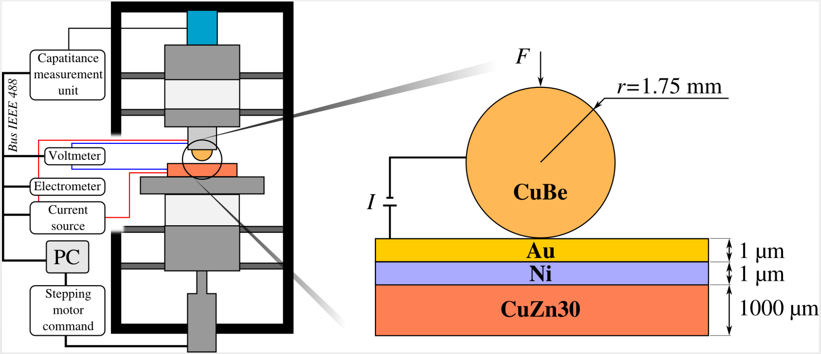
1. **Experiments on a sphere–plan system,** low-power (no heating effect)
2. **Axisymmetrical model** for mechanics and electrical conduction (2D-FE)
3. **Axisymetrical model and 3D simplified postprocessing** for mechanics and electricity (asperity based)
4. **Full-scale finite element analysis**

• Experimental set-up

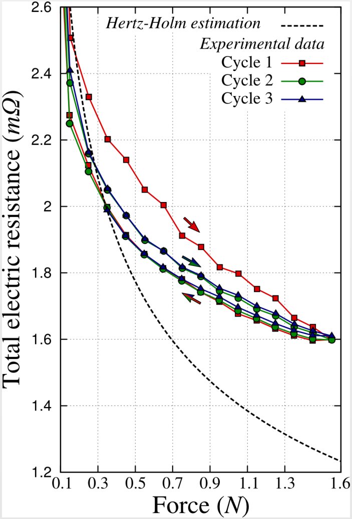


- 3 cycles load-unload
- Force-resistance $R(F)$
- Low power
- Brass plated by Ni and Au
- Elastic-plastic deformation
- AFM roughness data

• Measurements

- First load → initial plastic flow
- Subsequent cycles → plastic hysteresis
- System resistance $R = R_s + R_c$
- Hertz-Holm estimation

$$R_c = \frac{\rho^*}{2a} = \frac{\rho^*}{2}\left(\frac{4E^*}{3rF}\right)^{1/3}$$



ρ^* is the effective resistivity,
E^* is the effective elastic modulus

$$\rho^* = \frac{\rho_1 + \rho_2}{2}, \quad \frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$

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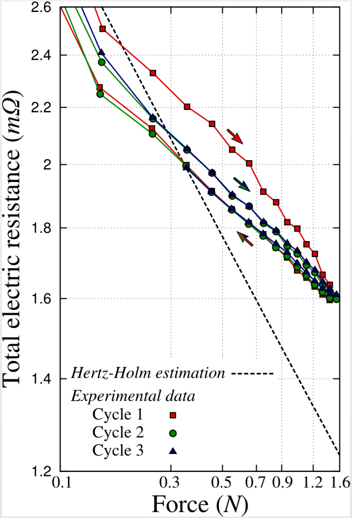


• How to improve the model $R_c + R_s = fct(F)$?

Improve R_c

- *2D Finite Element model (2D-FE):*

  ▷Sphere–plane with smooth surfaces, Au and Ni layers

  ▷Realistic elastoplastic behaviour (*Au, Ni, CuZn30, CuBe*)

Roughness effect on R_s

- *A multi-scale approach* using Greenwood's model

  ▷Axisymmetric model for mechanics and 3D asperity based postprocessing for mechanics and electricity

- *A full-field approach*

  ▷3D mechanical and electrical Finite Element (FE) solutions on representative surfaces

Oxidation effect on R_s

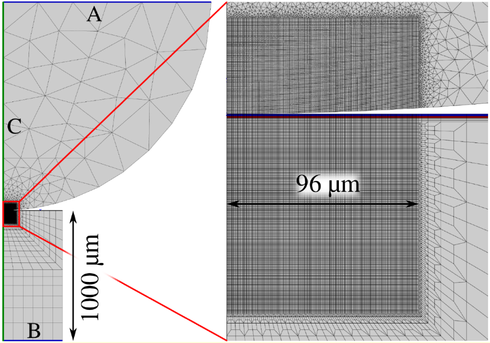
• Assumptions of the 2D-FE problem

Mechanical simulation

- Axisymmetric contact problem
- Explicit gold and nickel layers (1 μm each)

Electrical simulation

- Same FE mesh
- Assume perfect contact (no potentiel drop at the contact area)



- 90 000 nodes
- Quadratic tri. and quad. elmts
- Element size in the critical area, 0.5 μm

Elastic-plastic model

- Yield surface[1]:

$$f(\boldsymbol{\sigma}, \boldsymbol{X}, Y) = J_2(\boldsymbol{\sigma} - \boldsymbol{X}) - Y - \sigma_y$$

- Von Mises criterion:

$$J_2(\boldsymbol{\sigma} - \boldsymbol{X}) = \sqrt{\frac{3}{2}(\boldsymbol{s} - \boldsymbol{X}) : (\boldsymbol{s} - \boldsymbol{X})}$$

- Plastic strain:

$$\dot{p} = \sqrt{\frac{2}{3}\dot{\boldsymbol{\varepsilon}}_p : \dot{\boldsymbol{\varepsilon}}_p}, \quad \dot{\boldsymbol{\varepsilon}}_p = \dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}_{el}$$

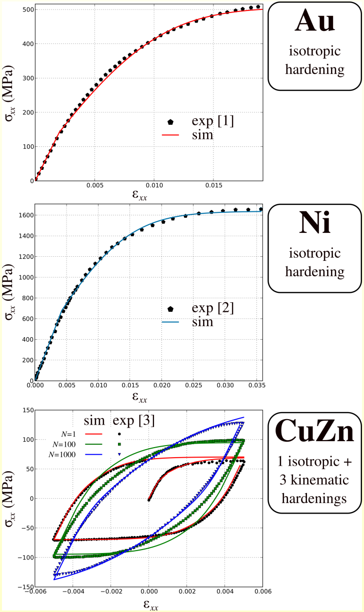
- Isotropic hardening:

$$Y = Q[1 - \exp(-bp)]$$

- Kinematic hardening:

$$\dot{\boldsymbol{X}} = \frac{2}{3}C\dot{\boldsymbol{\varepsilon}}_p - D\Phi(p)\boldsymbol{X}\dot{p}$$

$$\Phi(p) = \phi + (1 - \phi)\exp(-\omega p)$$



[1] $s = \sigma - \mathrm{tr}(\sigma)/3$ is the deviatoric part of the stress tensor.

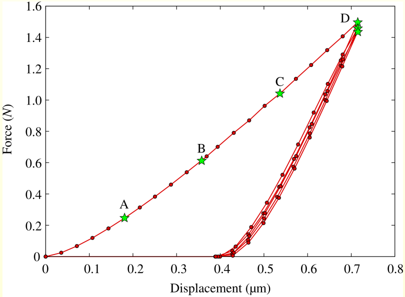
• Mechanical results of the 2D-FE model

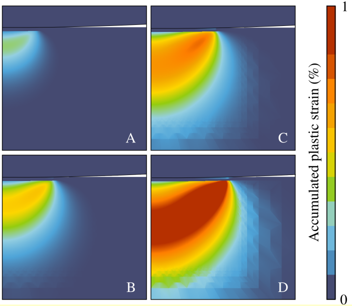
Force–displacement curve

- 1072 load steps
- The first cycle is critical, then steady state

Contours of the equivalent plastic strain field

- No plasticity in the nickel layer and in the CuBe ball
- $\varepsilon^p < 0.1\%$ in gold





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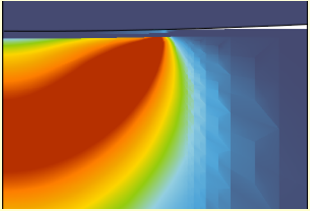
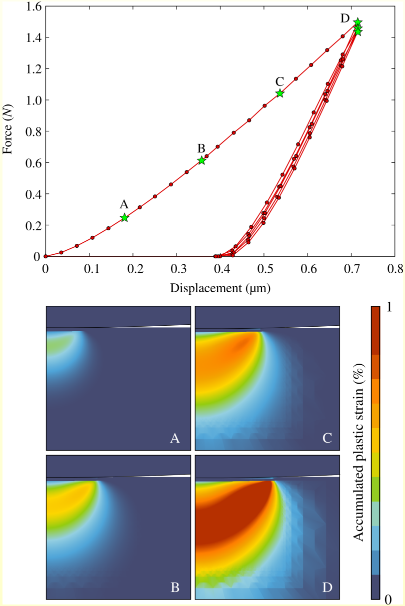


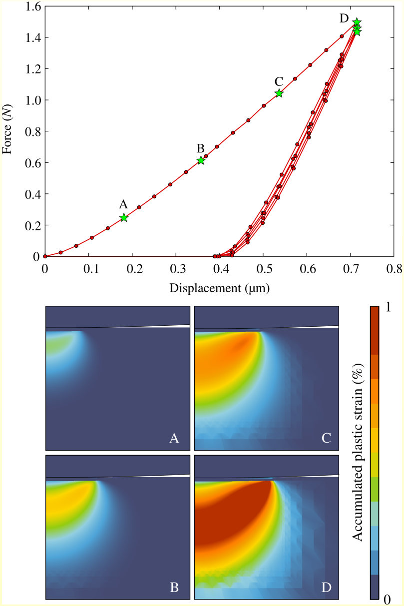


Force–displacement curve

- 1072 load steps
- The first cycle is critical, then steady state

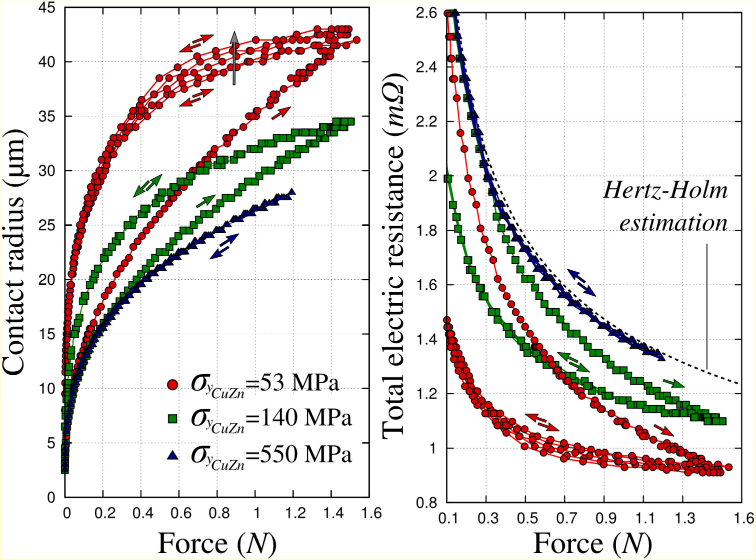
Electrical calculation

- For each step, create an electrical mesh with the four materials and the contact zone defined by the mechanical calculation
- Full field resolution of $\rho\vec{i} = -\nabla U$ with the relevant boundary conditions

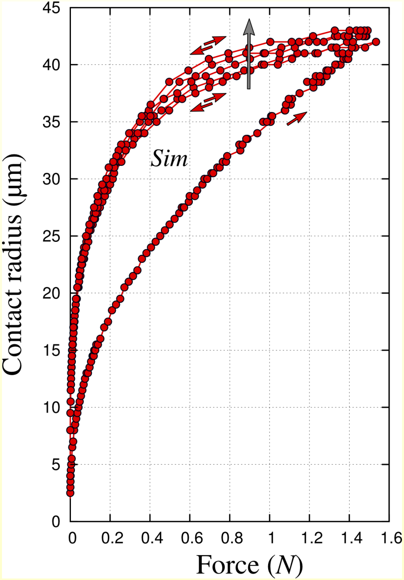


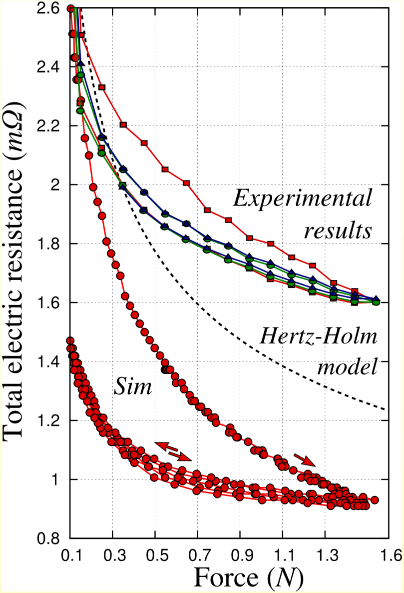
• Influence of the yield stress in brass

Contact radius and electrical resistance *versus* applied force



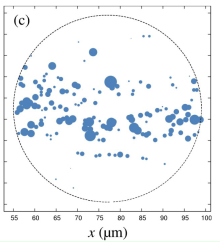
• Resulting curves with σ_y=53 MPa

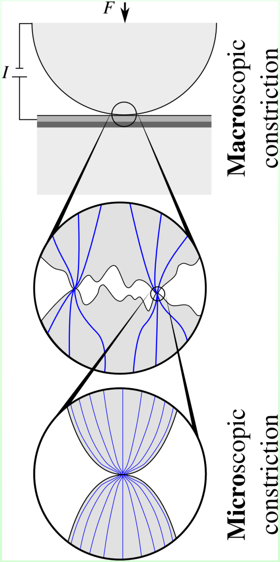




• Multiscale electrical contact

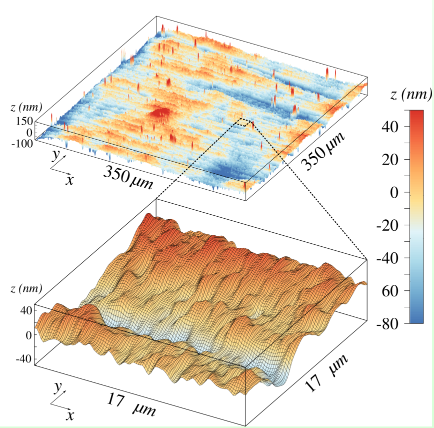
- **Macro**scopic constriction
  ▷Effect of geometry
- **Micro**scopic constriction
  ▷Effect of roughness
- **A need to characterize the position and the area of the spots for a given contact area (radius a, from 2D-FE)**





Roughness description

- Unlike a classical model, the actual roughness is
  - ⋆ *anisotropic*
  - ⋆ *not self-affine*
  - ⋆ *non-Gaussian*



Strategy of the model

- Knowing that the contact size is about 100 μm, extract (17 μm×17 μm) samples from the real surface
- Convert the continuous surface into a list of asperities
- Determine the contact spot number and size

• Multiscale model

Assumptions

- Smooth rigid ball
- Focus on first cycle

Algorithm

- Step 1 is performed once
- Step 2 and 3 repeated for 100 ($17\mu m \times 17\mu m$) surface samples

[1] Paggi & Ciavarella. *Wear* 39 (2010).

[2] Yastrebov, Durand, Proudhon & Cailletaud. *CR Mécan* 339 (2011).

[3] Greenwood. *J Appl Physics* 17 (1966).

Three sections in the model

1. 2D-FE mechanical analysis

   ⊳*contact pressure, contact area*

2. Iterative model for indentation of *elastically interacting*[1,2] elastic-plastic Hertzian asperities

   ⊳*contact morphology*

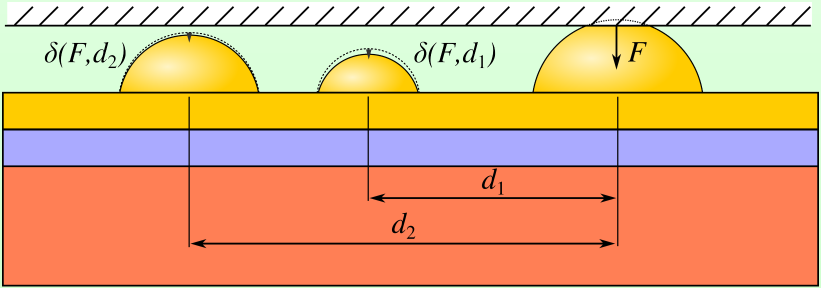
3. Greenwood model[3] for contact resistance

$$R_G = \frac{\rho^*}{2\sum a_i}\left(1 + \frac{2}{\pi}\frac{\sum\sum_{i\neq j} a_i a_j / d_{ij}}{\sum a_i}\right)$$

• Three-level model: asperity model

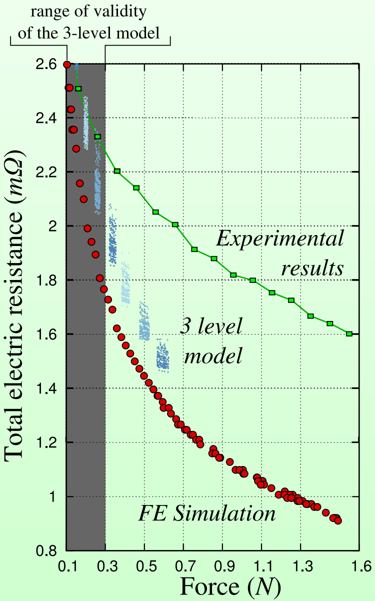
- Elastic-plastic transition:
  Hertz equation if $F_i/\pi a_i^2 < 3\sigma_y$, otherwise $F_i = 3\sigma_y \pi a_i^2$
- Iterative computation scheme with elastic interaction between contacting asperities $\Delta z_j \sim \sum_i F_i/d_{ij}$

$$a_i = \left(\frac{3rF_i}{4E^*}\right)^{1/3} \qquad F_i = \frac{4}{3} r^{1/2} E^* \delta^{3/2}$$



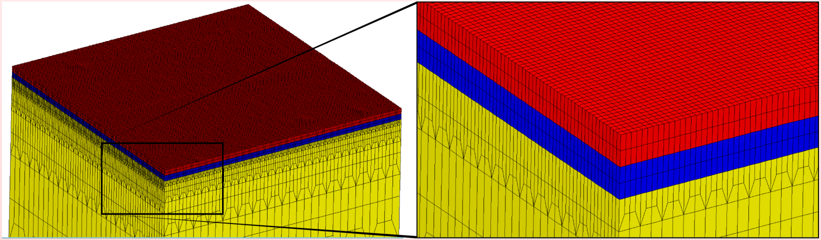
• Three-level model: comparison

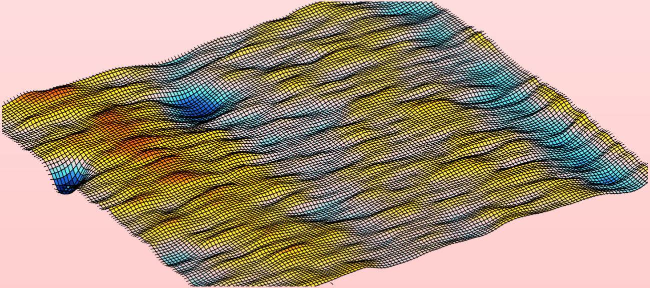
- 3-level model yields realistic results
- Valid for light contact forces
- For higher loads, approximation of roughness by asperities is not valid
- *The problem of surface state (oxidation ?) is still pending*



• Geometry and mesh for the full-scale FE simulation

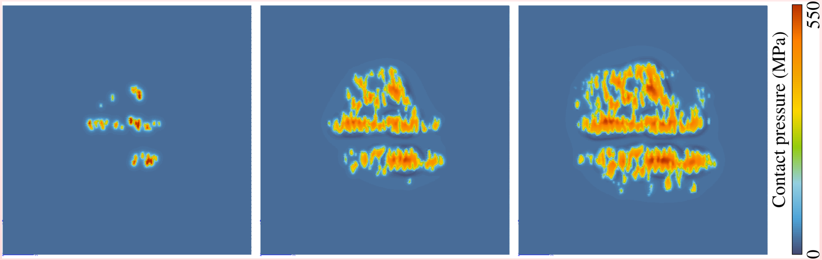
- Mapped roughness in contact with a rigid sphere
- FE mesh ≈ 1 500 000 dofs



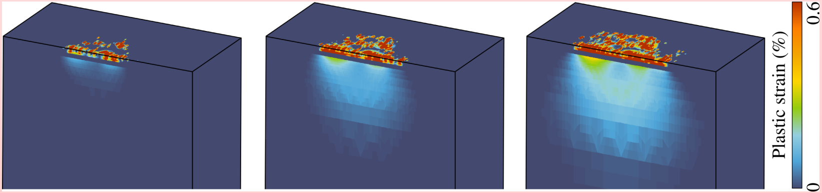


• Results of the full-scale FE simulation

Evolution of the contact pressure

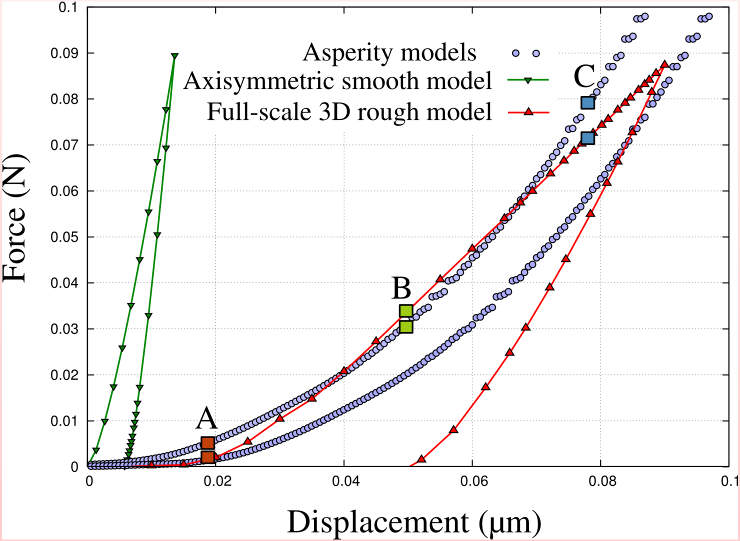


Equivalent plastic strain in gold and brass



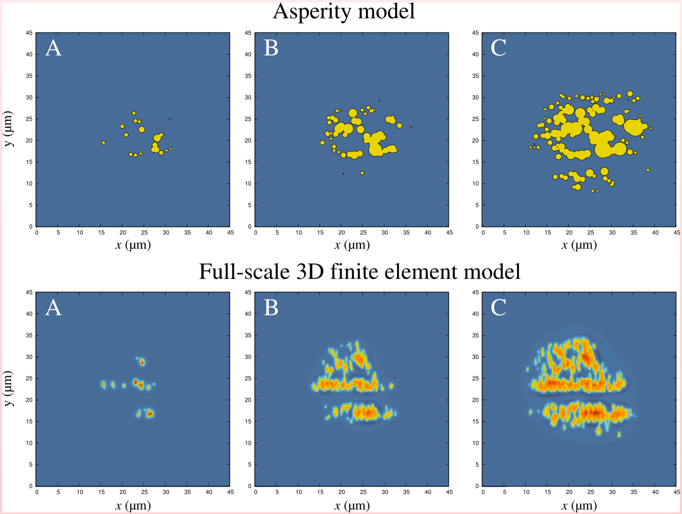
• A synthesis of 2D and 3D models

Force–displacement curve



• Comparison of the contact surfaces with the simplified and the full-field models

Force–displacement curve



• Conclusion and prospects

- **3D-rough far from 2D-smooth !**

  ▷Different loading curves, different local plasticity in layers

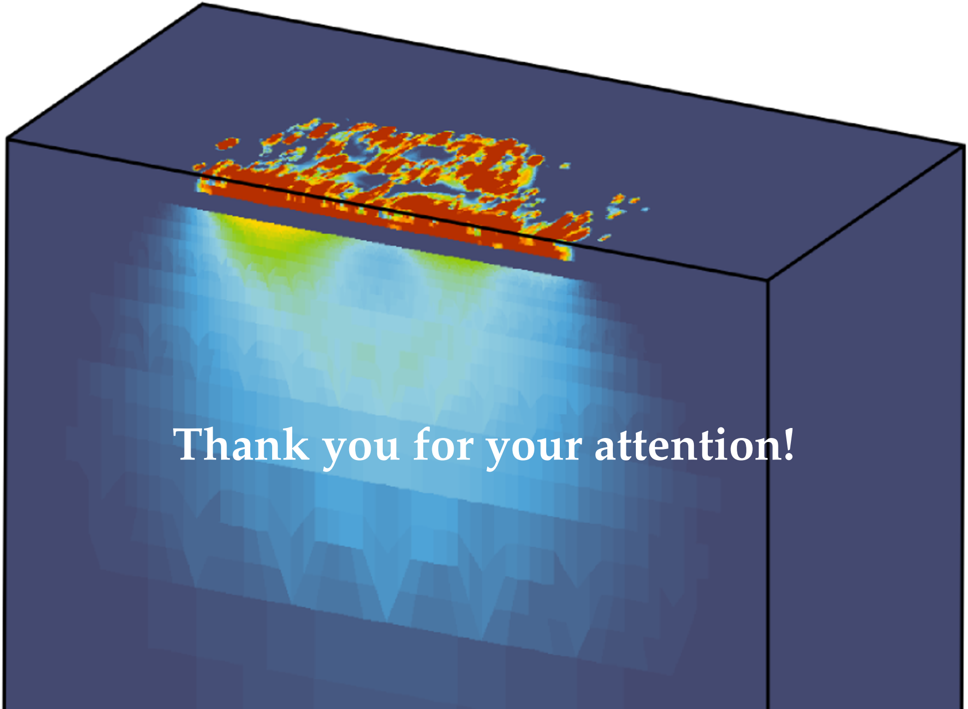
- **Bad/good results for the simplified multiscale model**

  ▷Good for the loading curve,

  ▷Bad for the morphology of the contact surface, that explains its limited validity

- **Full scale electro-mechanical simulations with adequate material models mandatory for industrial contacts**

  ▷Electrical calculations to be made



Thank you for your attention!

Roughness description

- Classical model is inappropriate:
  isotropic, Gaussian, self-affine
- Actual roughness is
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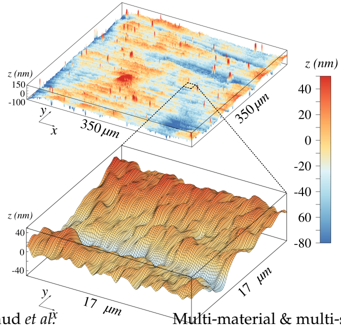

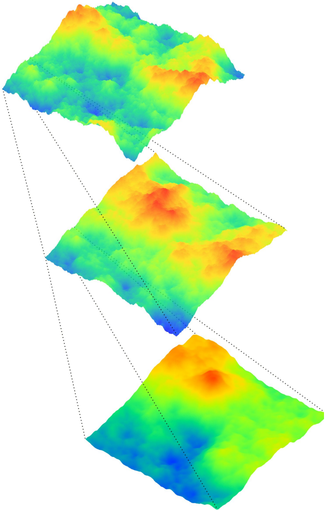

Isotropic, self-affine, Gaussian model surface
$H = 0.8$

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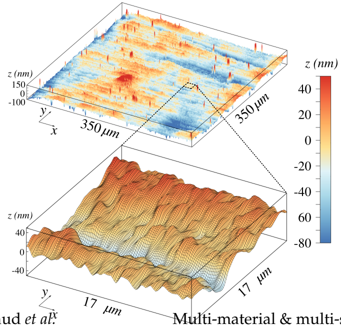
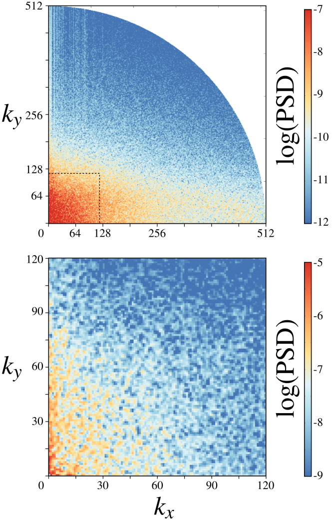


★ **Anisotropic**



Power spectral density of the plate surface

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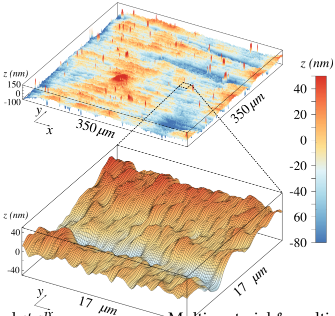
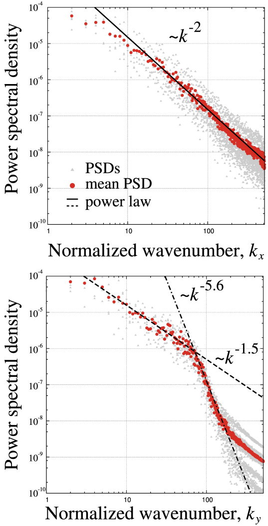


★ Not self-affine



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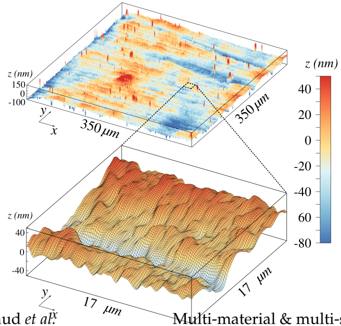
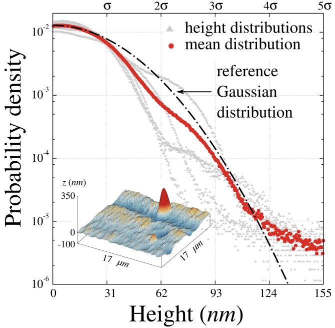


★ Non-Gaussian



High distribution

• Illustration of asperity flattening