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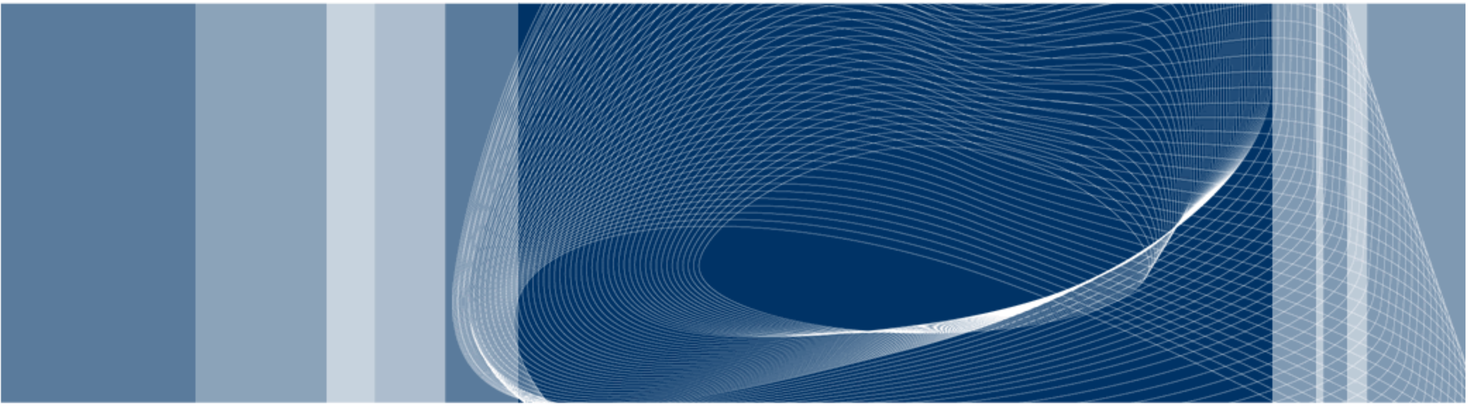

A top-down, three-scale numerical analysis of wafer-to-wafer metallic bonding

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Thermo-compression bonding

It is a simultaneous application of pressure and temperature to seal the cavity where MEMS are placed.

This allows bonding under conditions otherwise not achieved by one parameter alone.

The following steps are typically followed for wafer to wafer bonding:

1 – in the bonding chamber the temperature is increased until the target temperature is reached ($T_{target}<T_{melting}$);

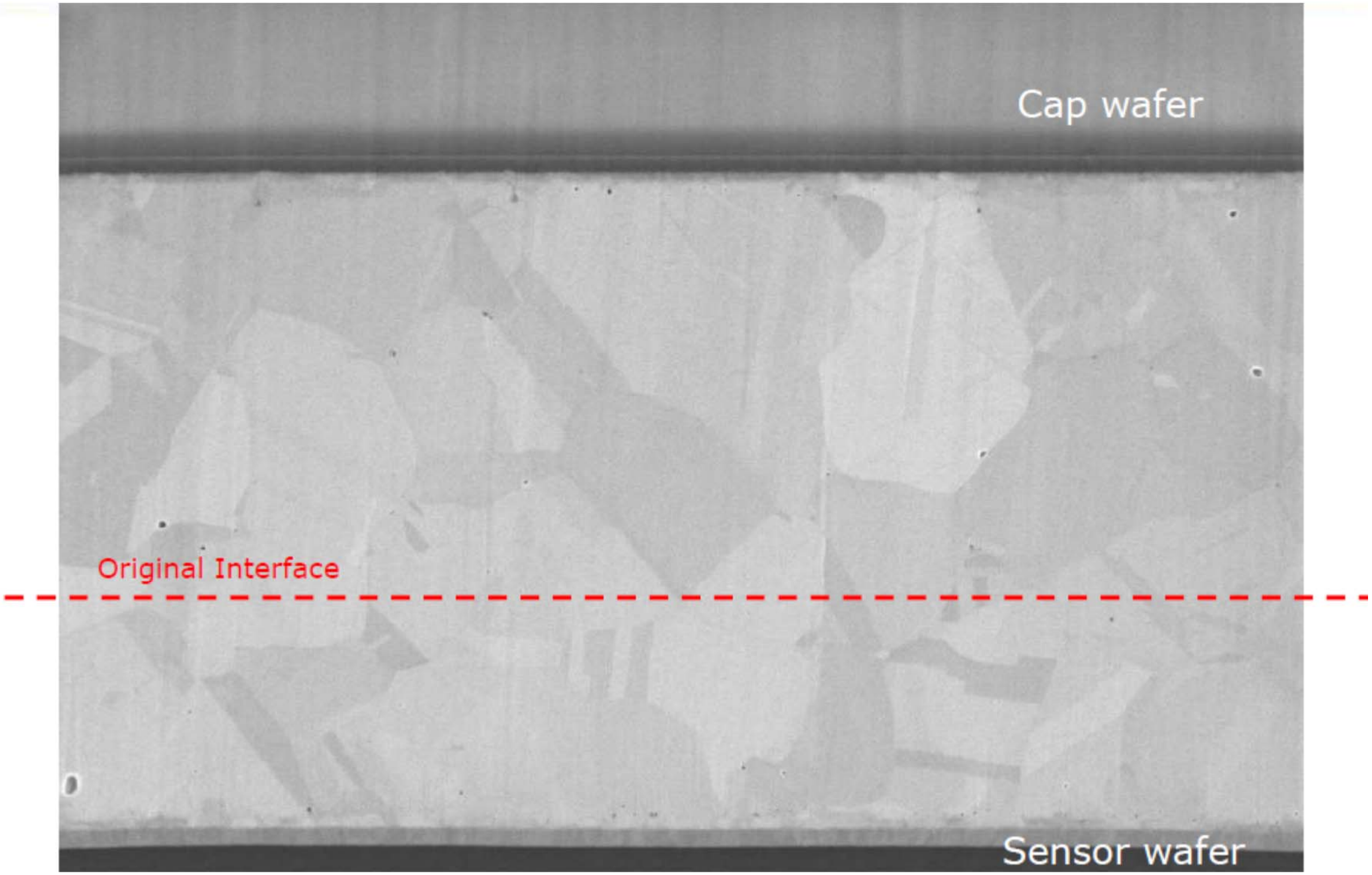
2 – the system is maintained at constant temperature;

3 – a pressure is applied externally through a rigid hydraulic jack to the upper surface of the wafer constituting the cap while the base wafer is fixed to a support.

During step 3 very complex phenomena could occur, such as grain growth and recrystallization partially driven by local stress.

As a first attempt to gain knowledge for design, we stick here to a purely mechanical approach.

Typical bonding interface after re-crystallization



The original grains increase their diameter and move, even across the original interface. The figure shows a transversal section across the metal sealing rings.

Hypotheses of the whole procedure

1. Assuming to be at constant thermal conditions, the upper hydraulic jack imposes a uniform pressure on the wafer.

2. At least three-scales (macro-, meso-, and micro-scale) are involved in the purely mechanical response.

2a. At the macro-scale the **whole wafer** response is considered.

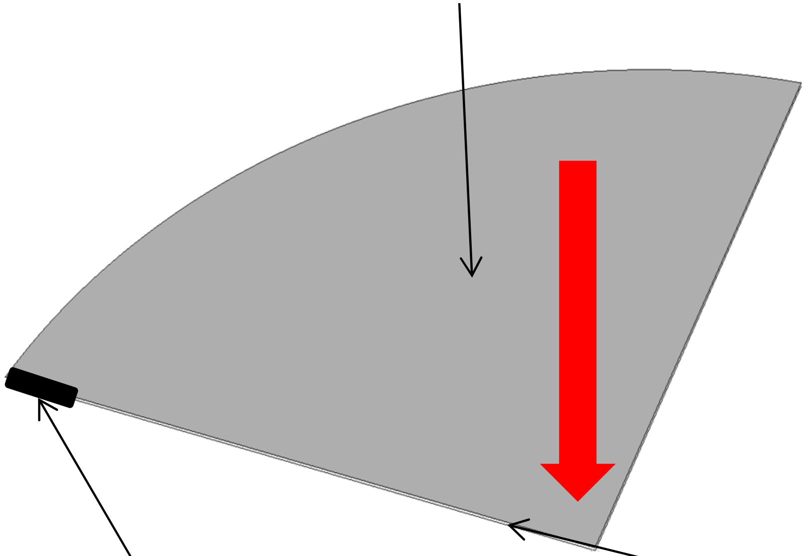
2b. At the meso-scale the **single die** response is considered.

2c. At the micro-scale the **local surface** topology is taken into account.

3. The area entered into contact in 2c with the applied pressure from 2b provides a local (rough) measurement of the bonding efficiency.

Macro-scale simulations

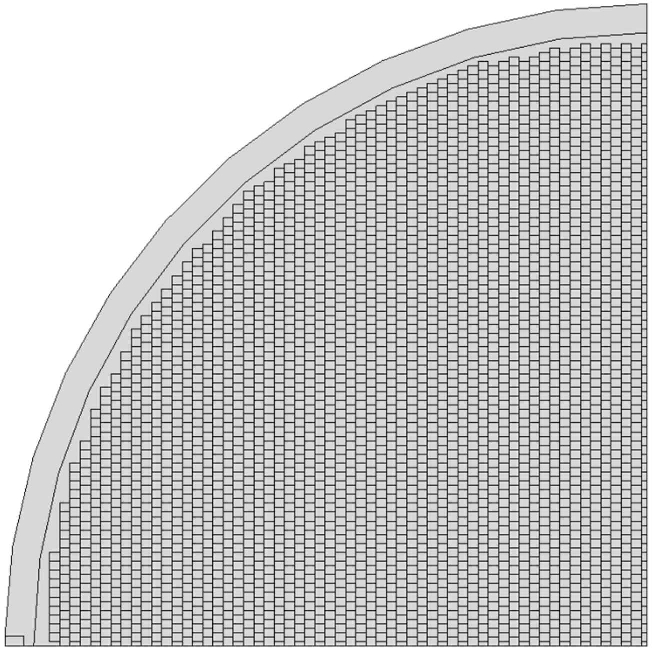
Input: maximum load *P* from the machine.
Output: force imposed at each die connection.



A rigid plate simulates the rigid hydraulic jack

A deformable plate
simulates the cap/die wafer.

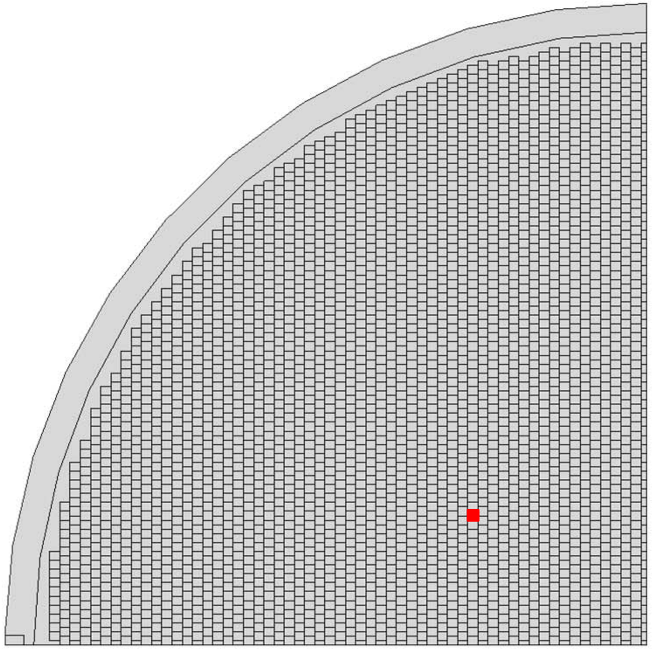
Die wafer is clamped
to avoid rigid body
movements.



Die nominal positions are reproduced on the plate.

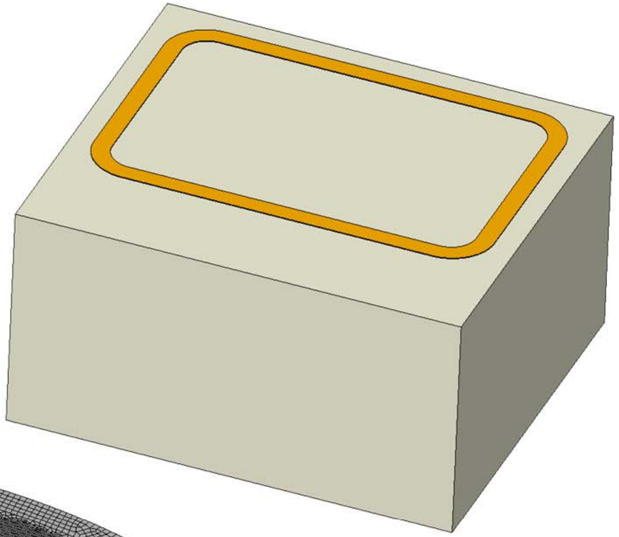
In order to evaluate the influence of supports on pressure distribution we need a simplified formulation of the reaction-displacement law.

Macro-scale analysis



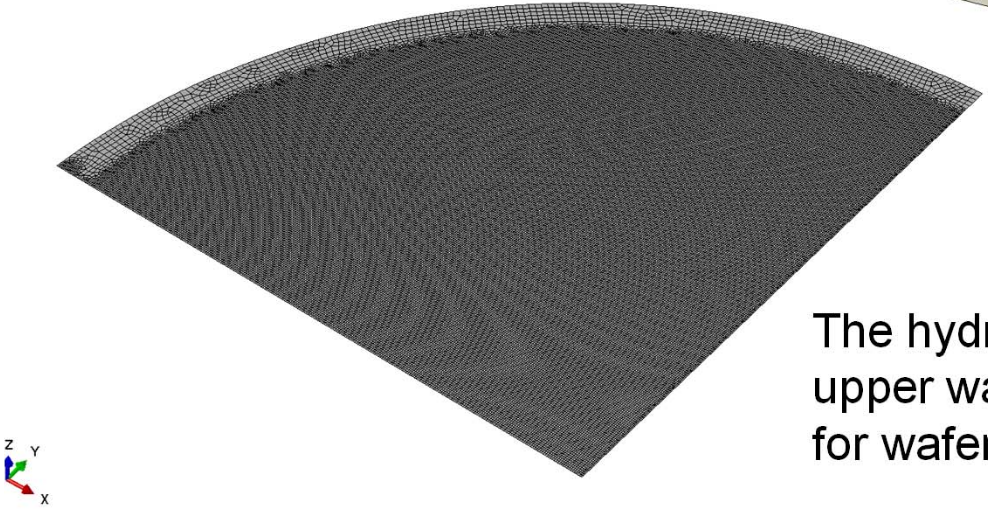
Subdivision of the wafer geometry so that each metal ring is modeled as:

$$k = \frac{EA}{t}$$



=

1. linear spring;
2. nonlinear spring.

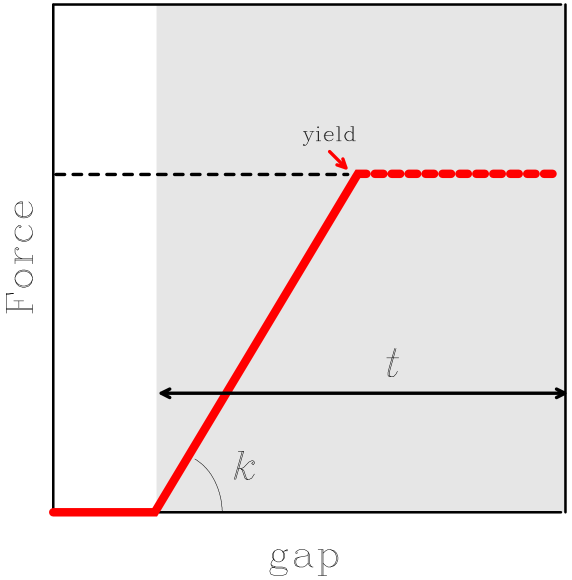


The hydraulic jack is modeled as rigid plate contacting the upper wafer. Structural elements are used: plate elements for wafers and springs for metal rings.

Macro-scale analysis

Orthotropic elasticity is adopted for silicon in the wafers.

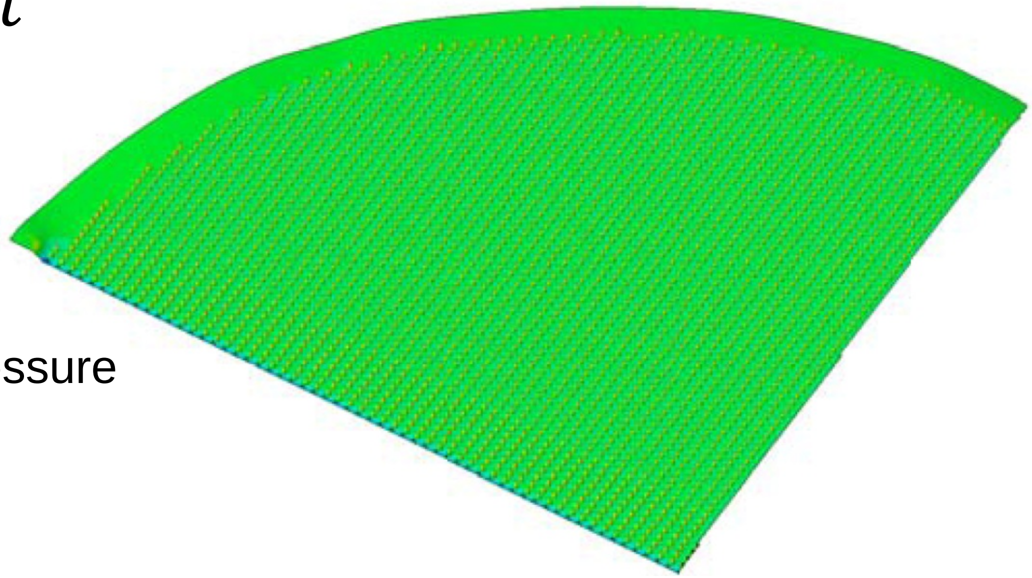
Springs' nonlinear behavior is set as in figure.



The thickness is changed deterministically or stochastically to represent varying metal layer thicknesses along the wafer.

The stiffness is set as:

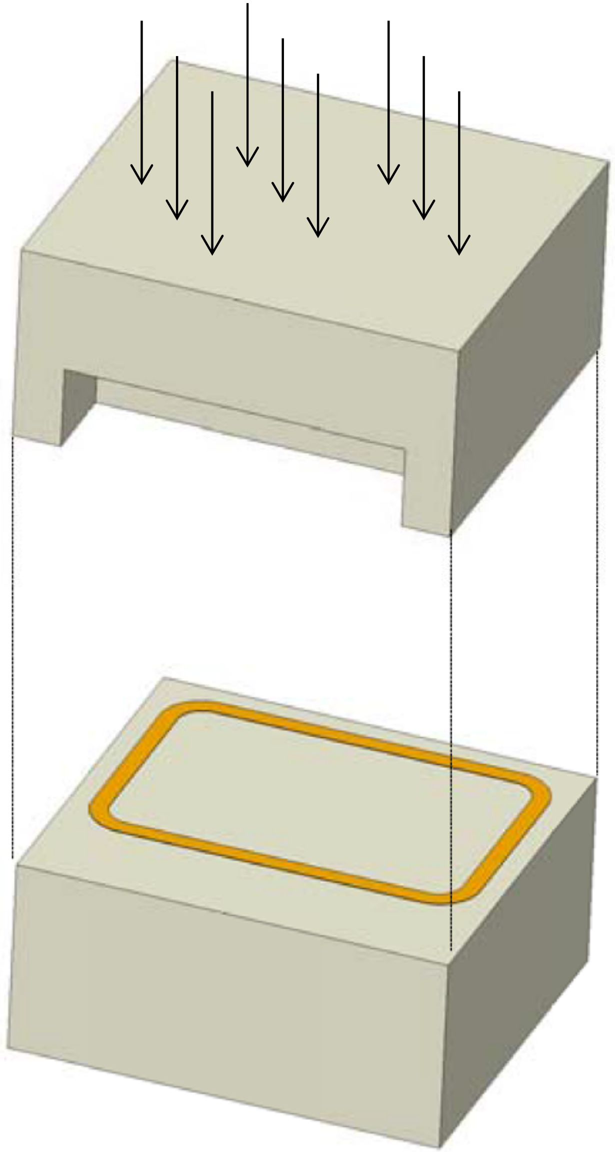
$$k = \frac{EA}{t}$$

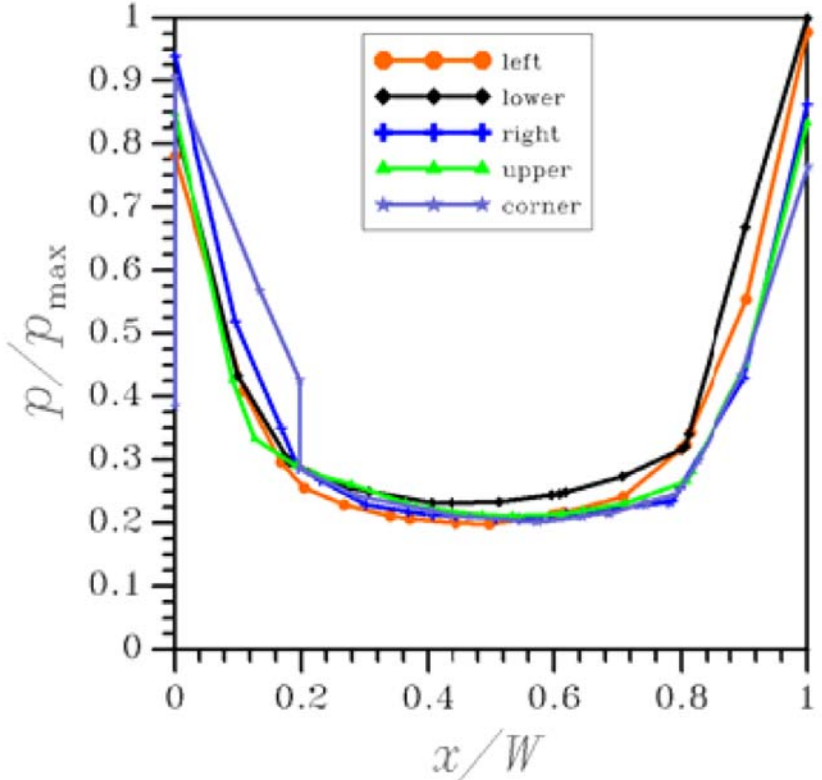


Local spring force will become the pressure applied at the meso-scale.

Meso-scale analysis (1)

Assuming a uniform pressure on the top die surface, calculate the pressure distribution along the metal rings. These local pressures will be the input for the micro-scale analyses.

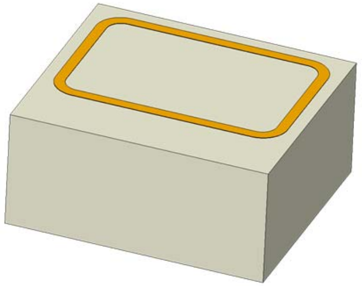


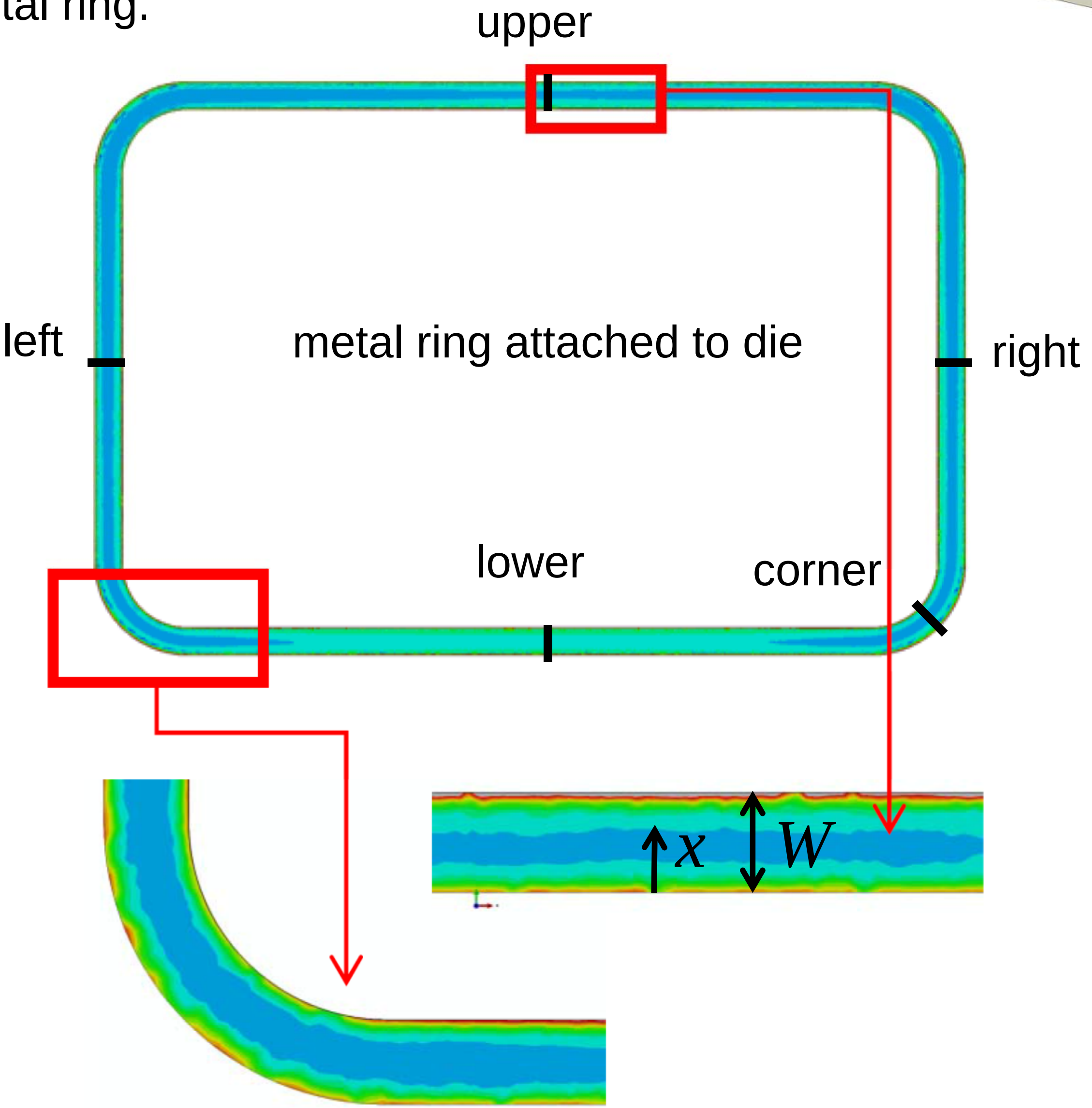


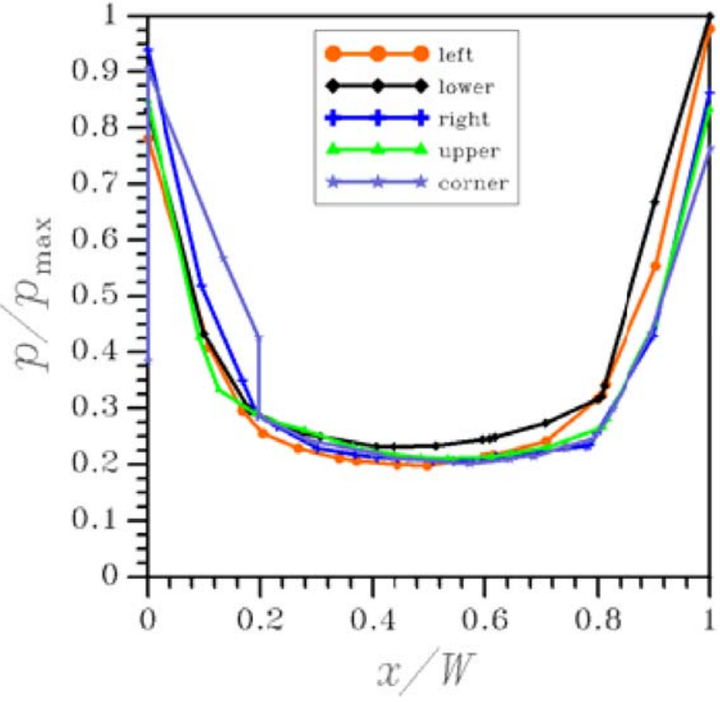
Meso-scale analysis (2)

Orthotropic elasticity is adopted for silicon in the wafers.

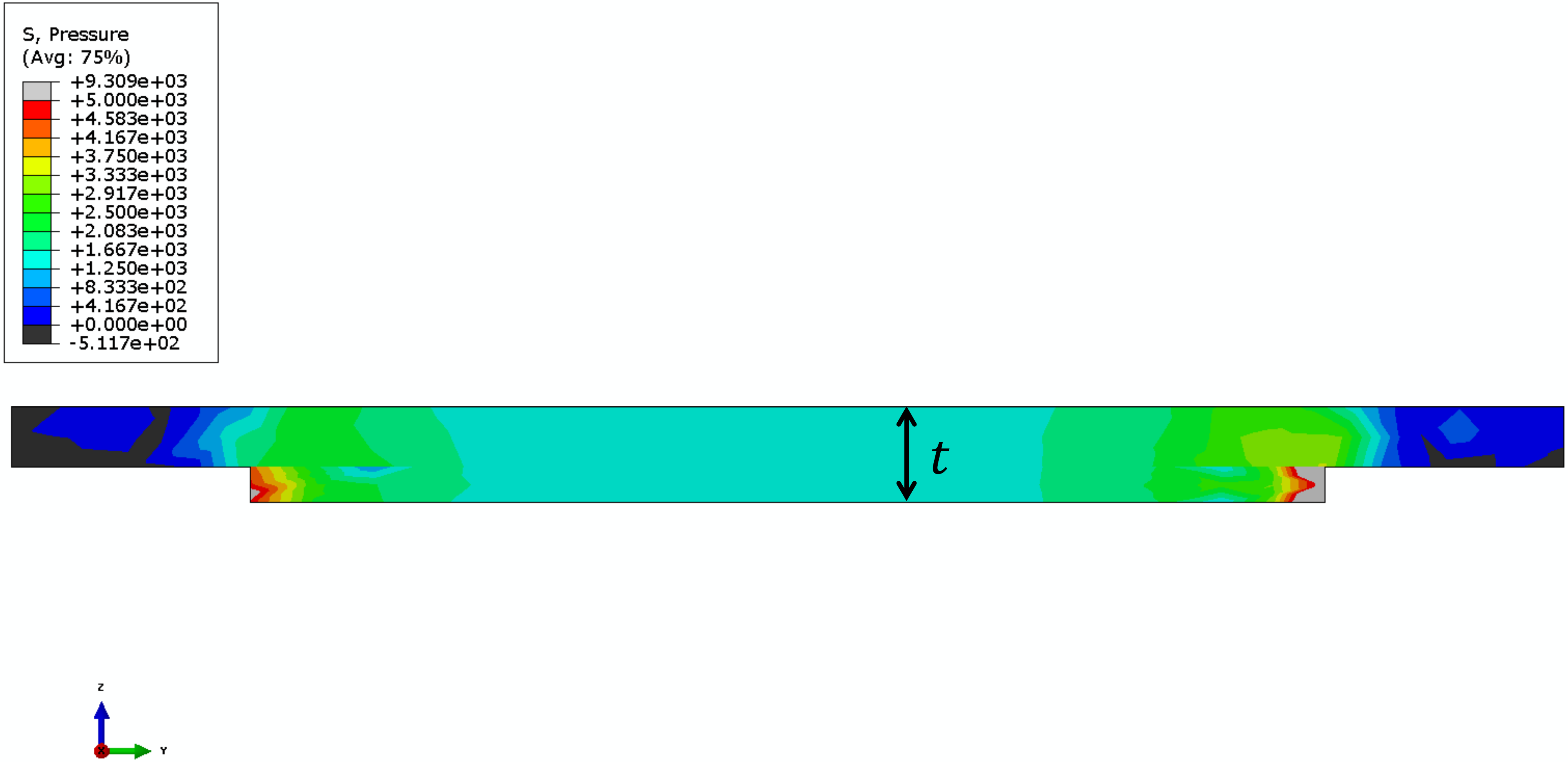
An elastic-plastic behavior is assumed for the metal ring.



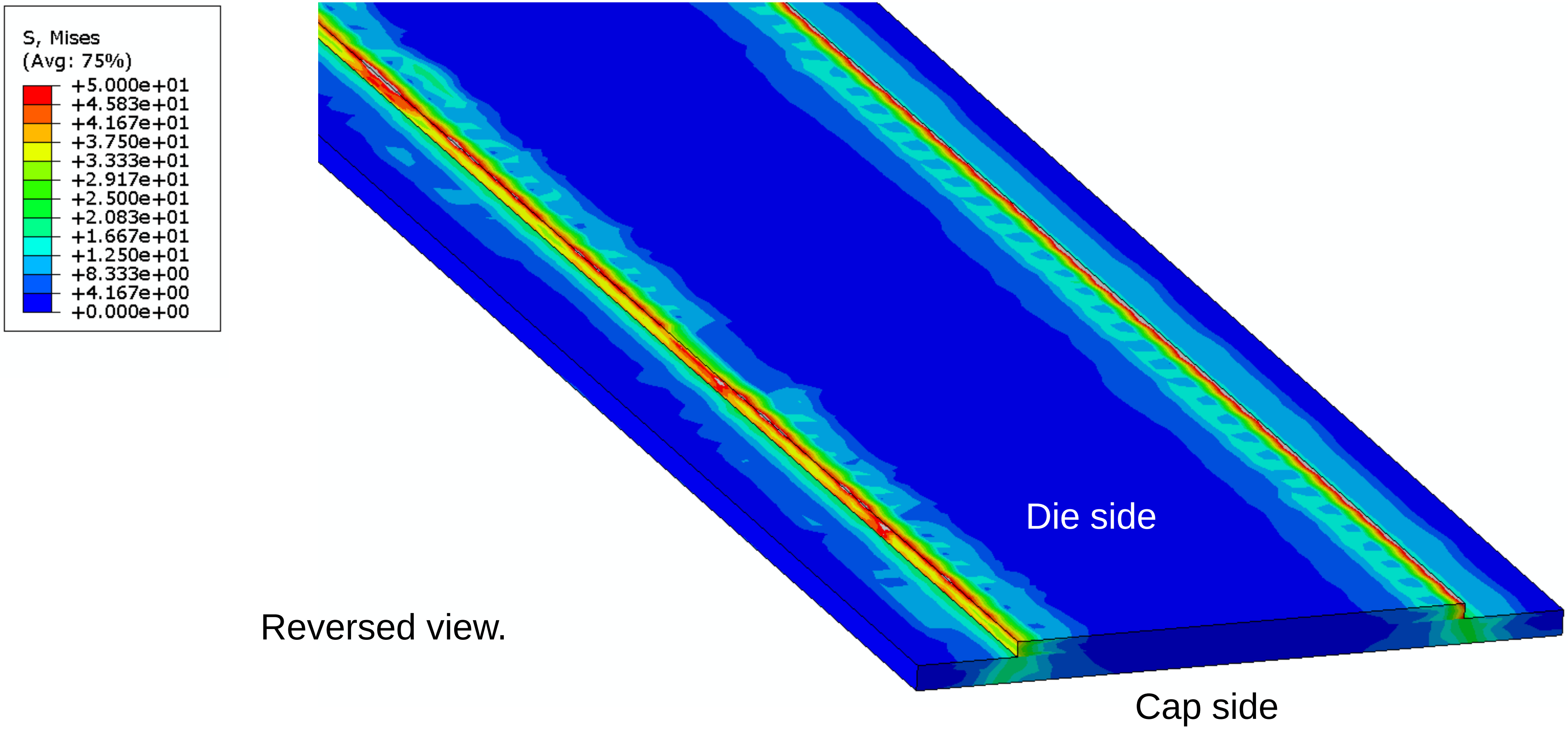




Meso-scale, transversal section of metal ring

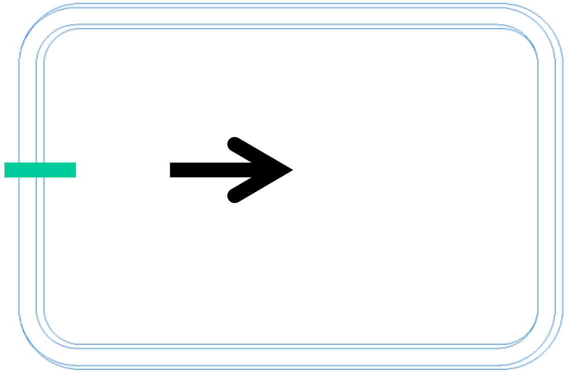


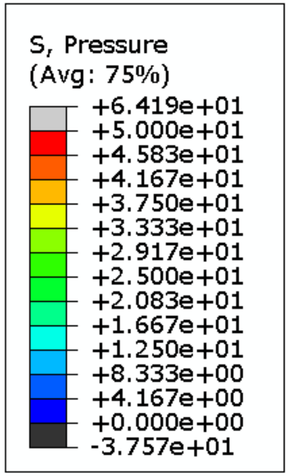
Meso-scale, transversal section of metal ring

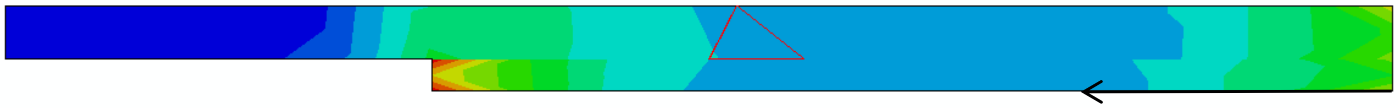


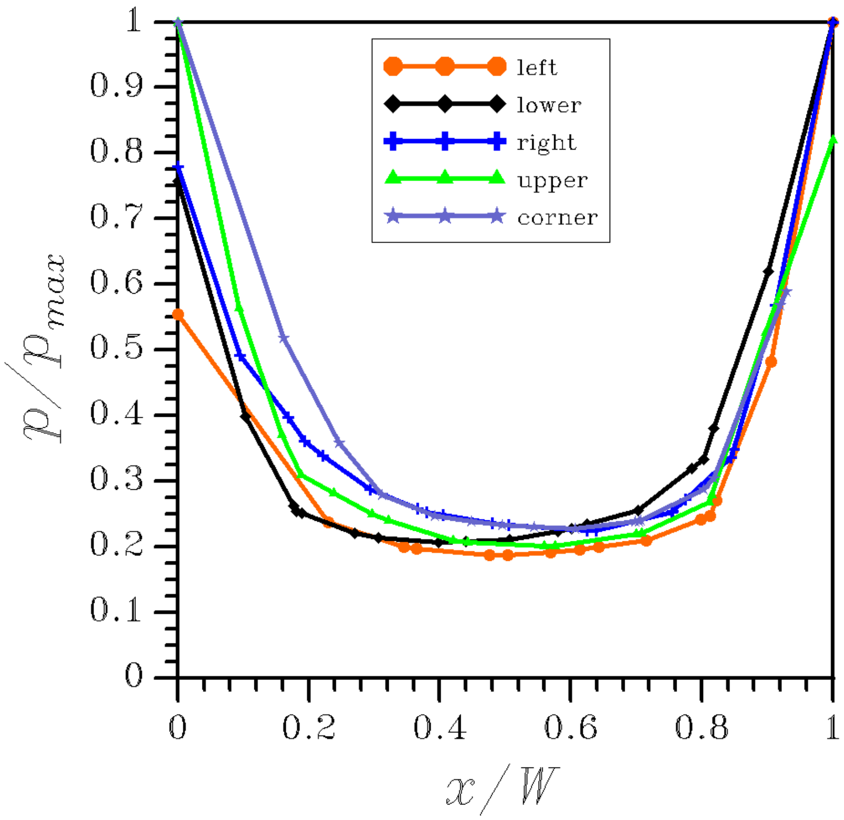
Reversed view.

Meso-scale, mis-alignment along X

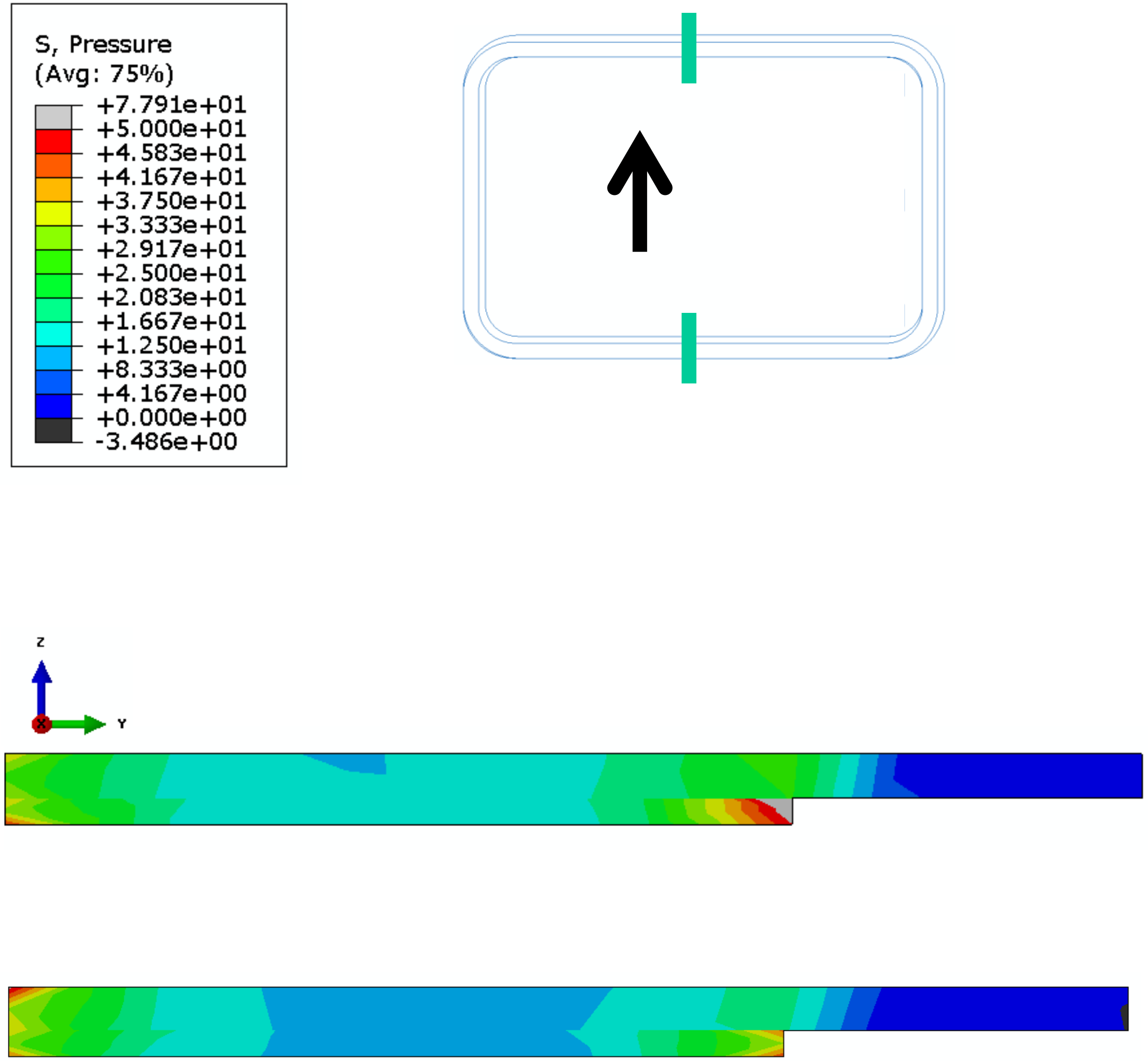


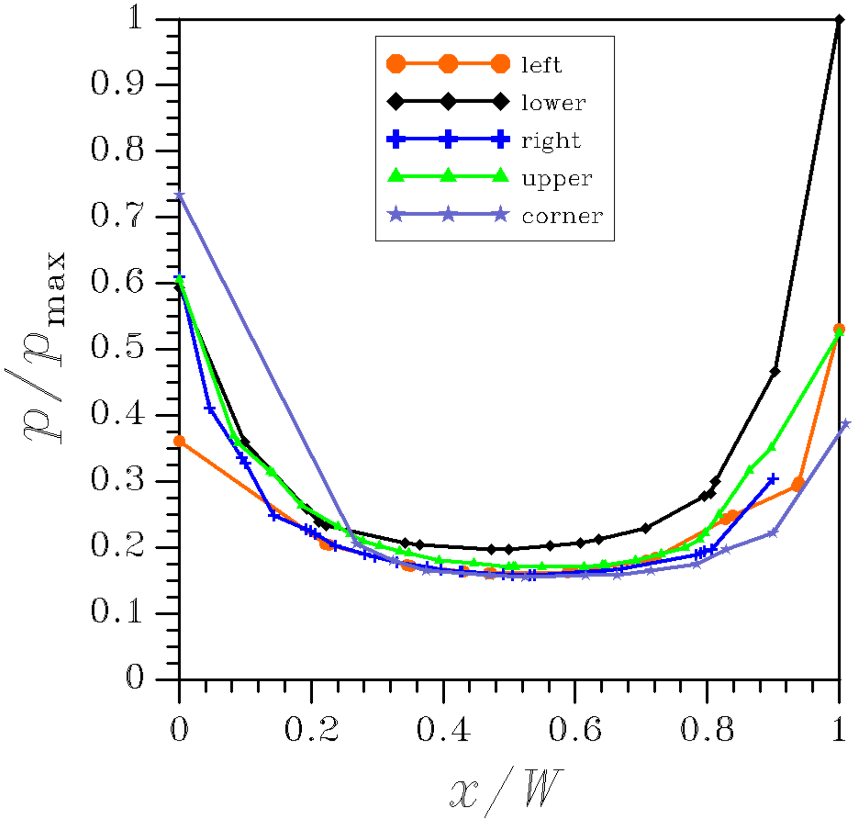




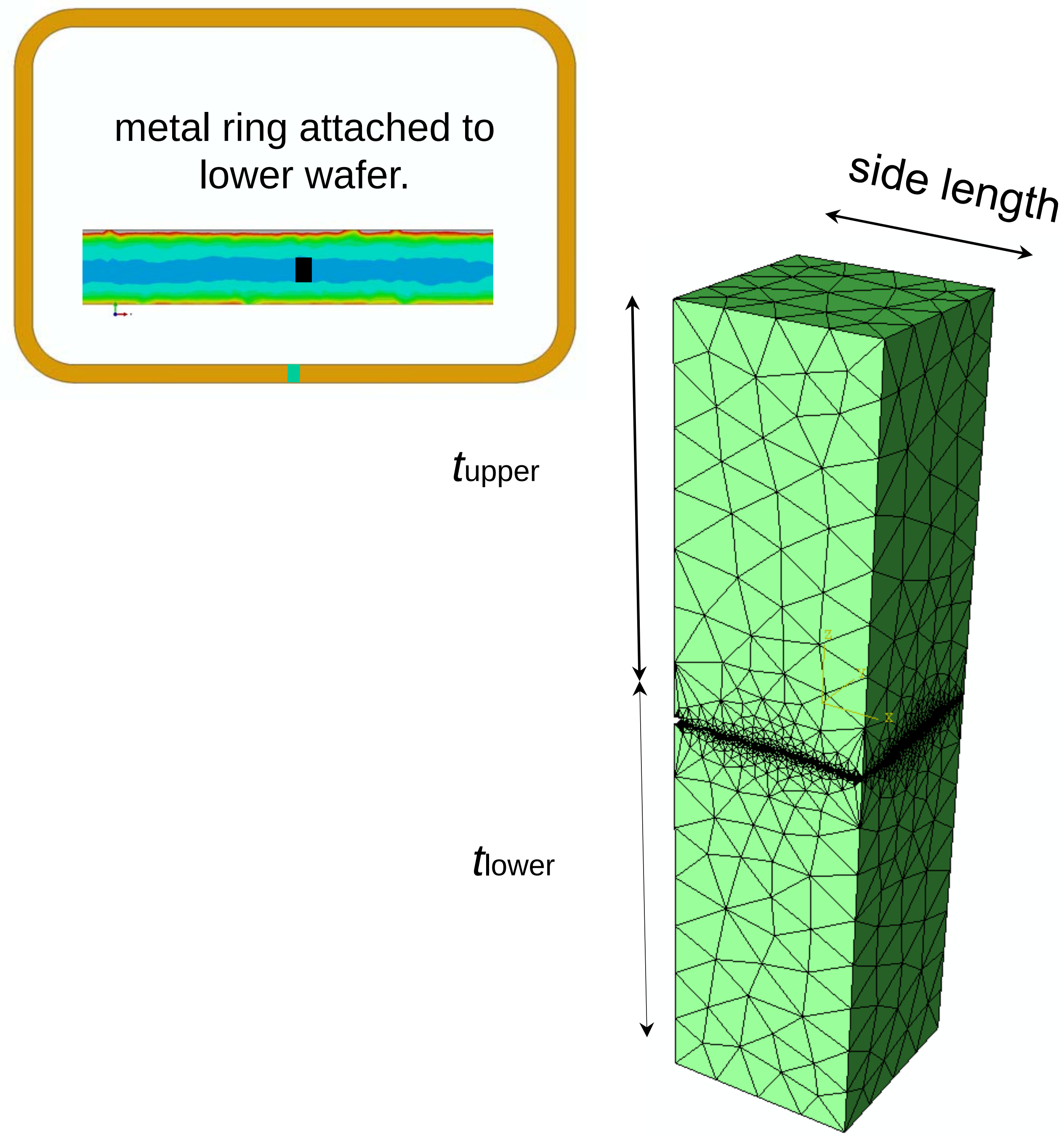


Meso-scale, mis-alignment along Y





Micro-scale analysis (1)

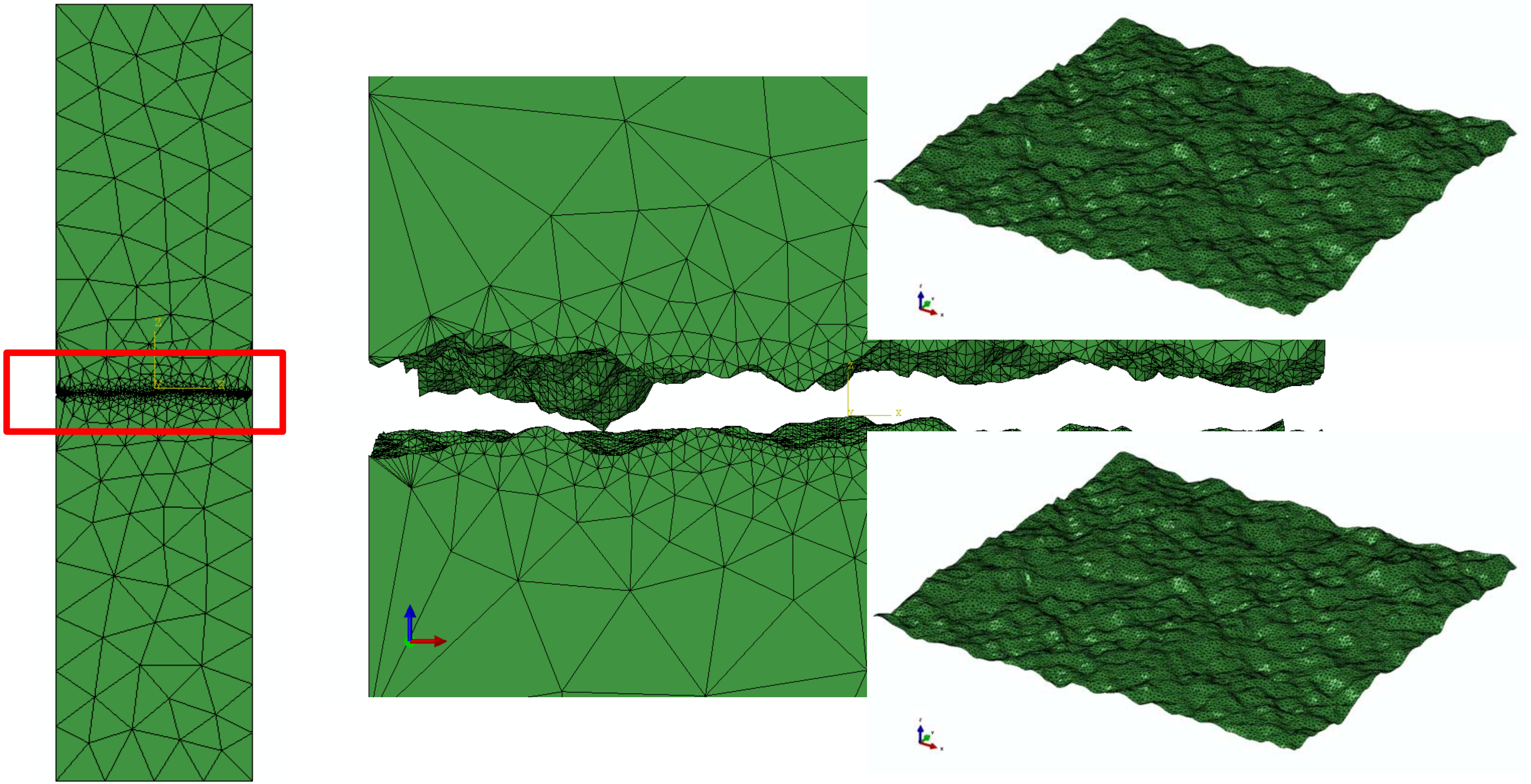


Input: local pressure from meso-scale analyses.

Boundary conditions: fixed bottom surface, no normal displacement over the vertical surfaces.

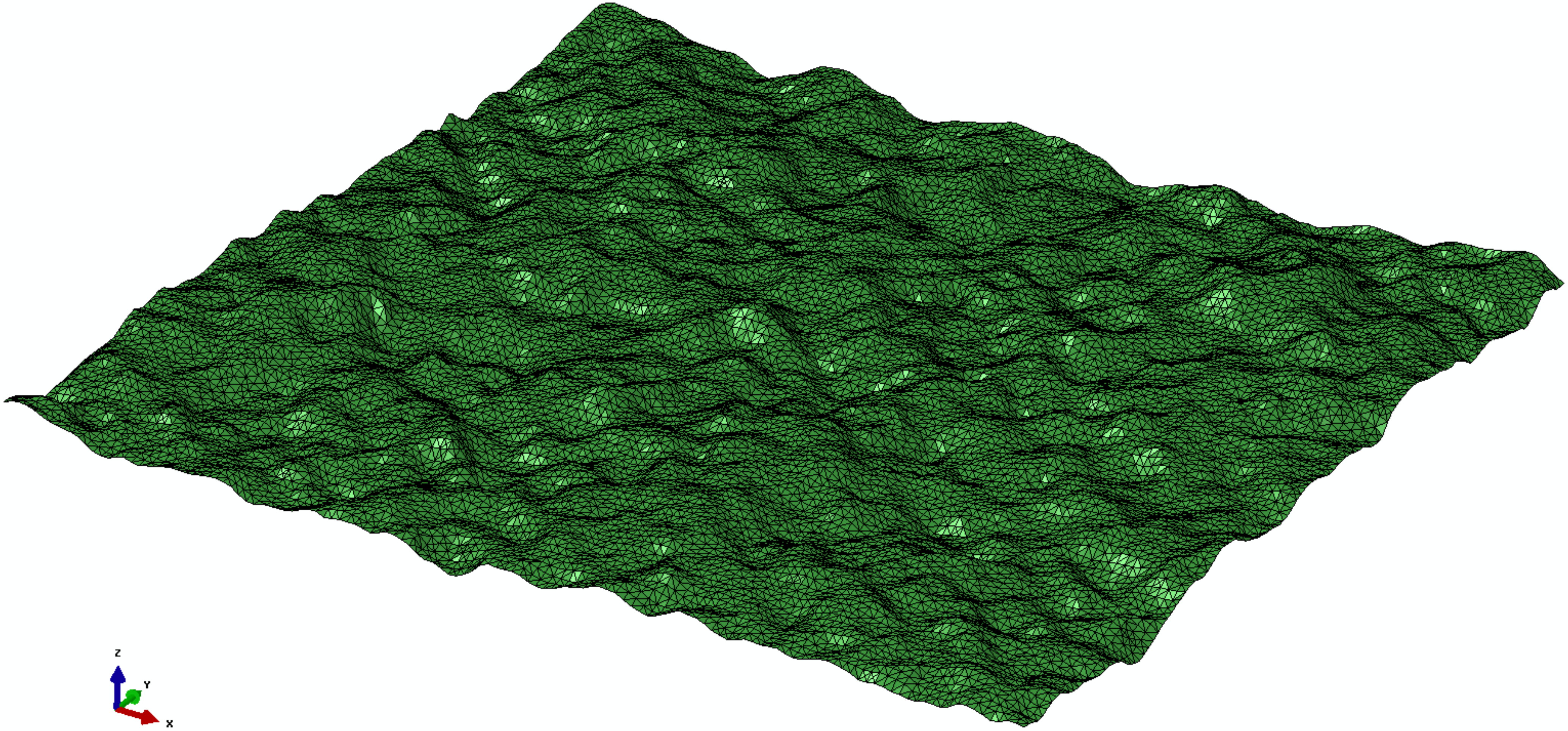
Output: percentage of area into contact, stresses.

Microscale analysis (2)



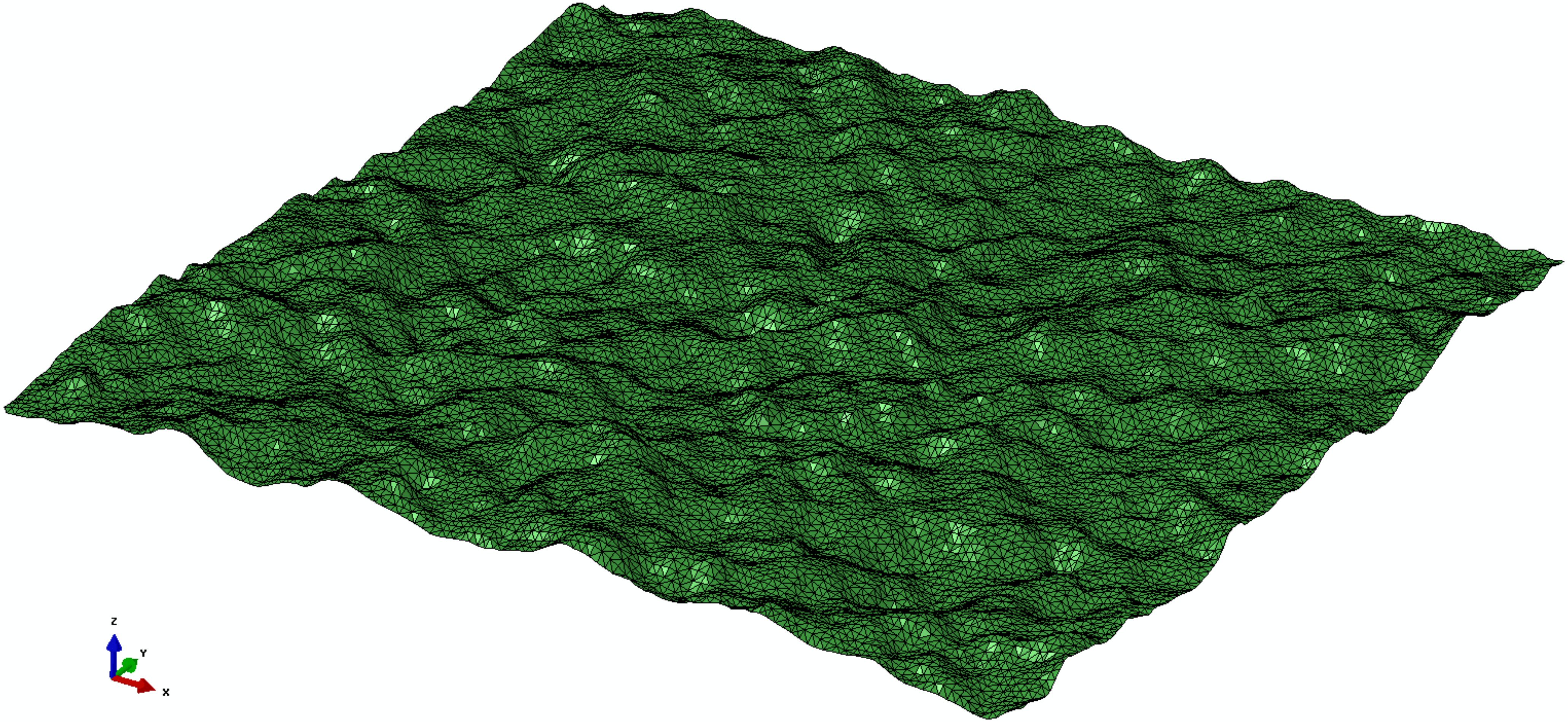
$rms = 10$ nm.

Micro scale local surfaces (1)



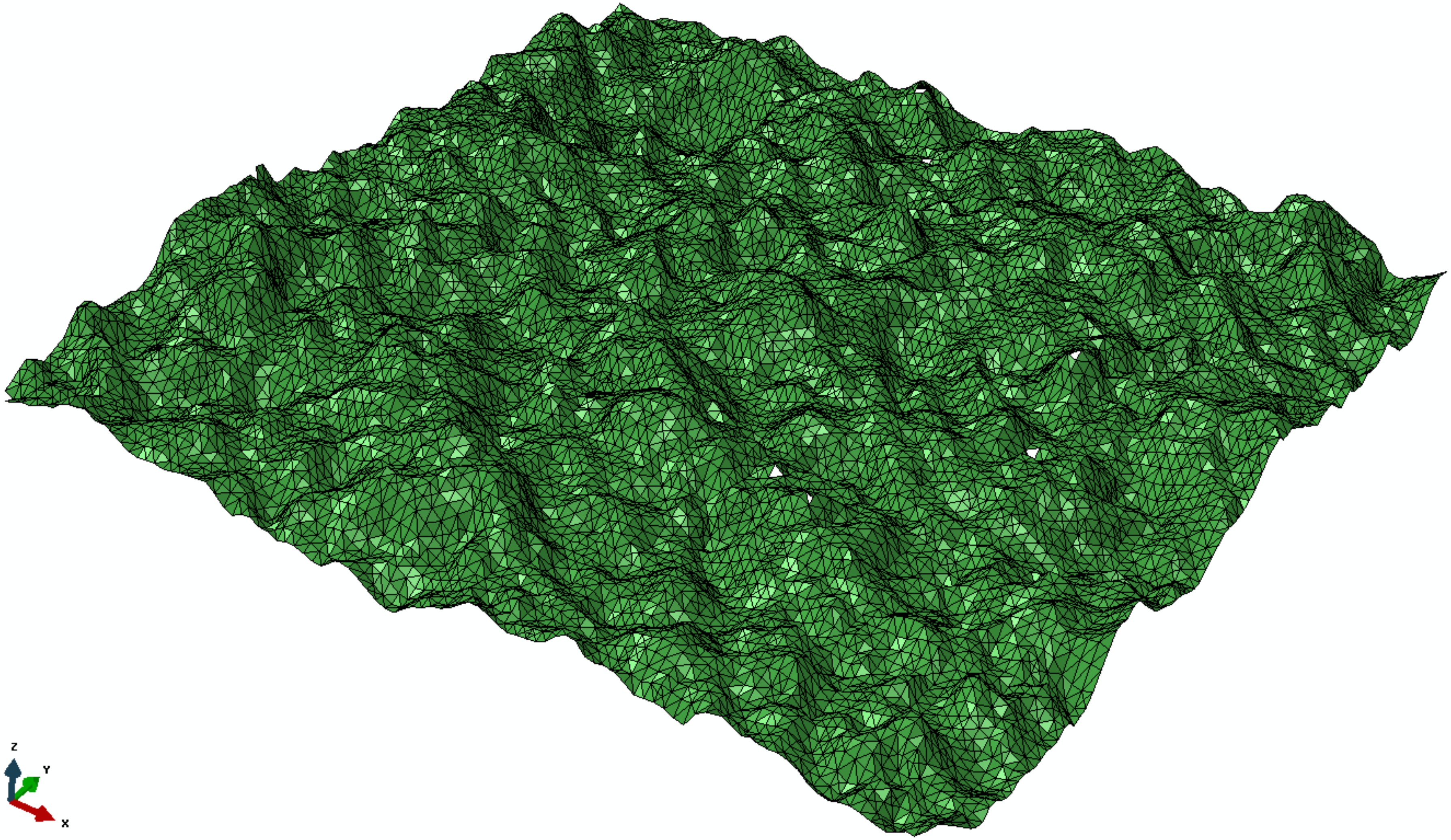
bottom surface, rms = 10 nm

Micro scale local surfaces (2)



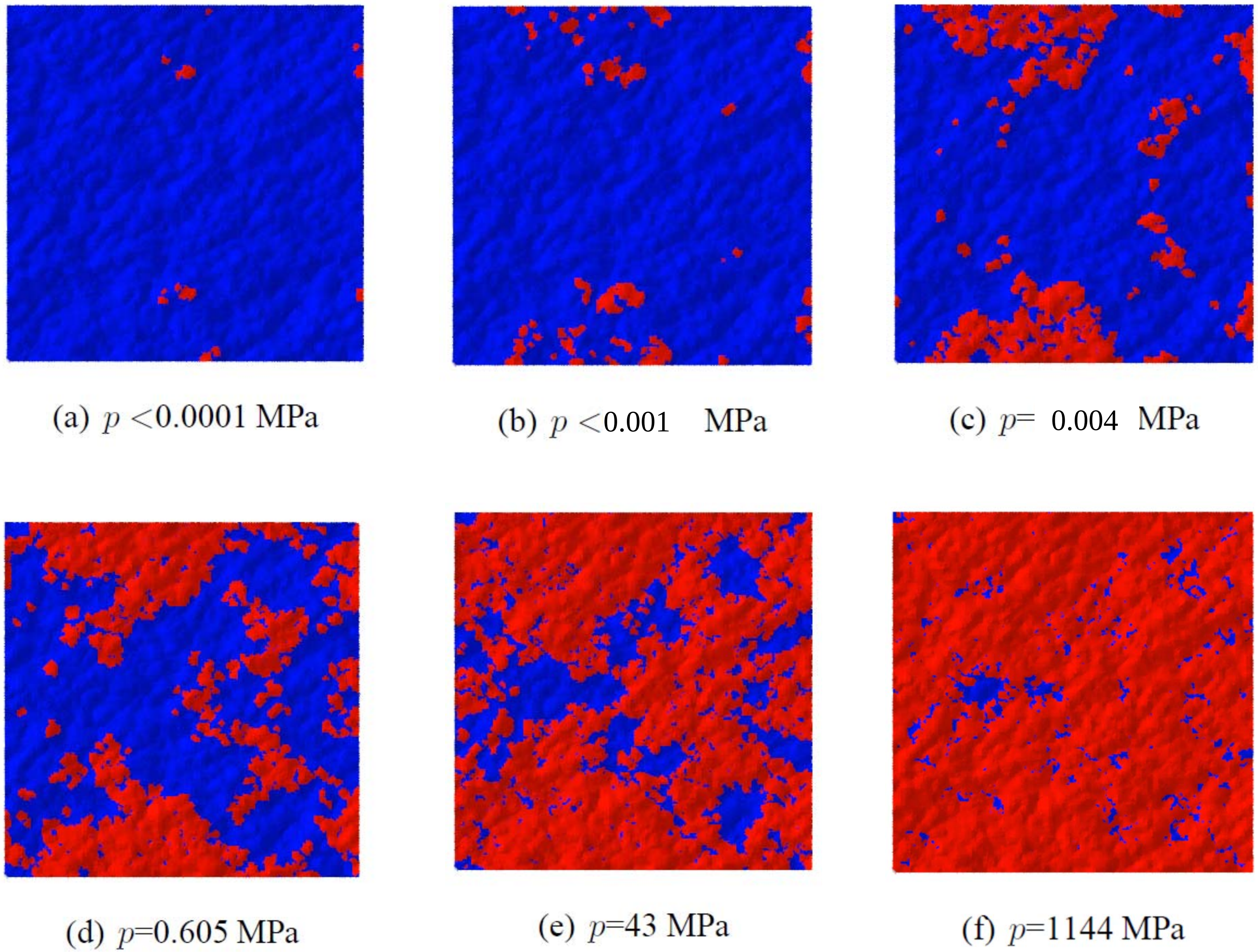
top surface, rms = 10 nm

Micro scale local surfaces (3)



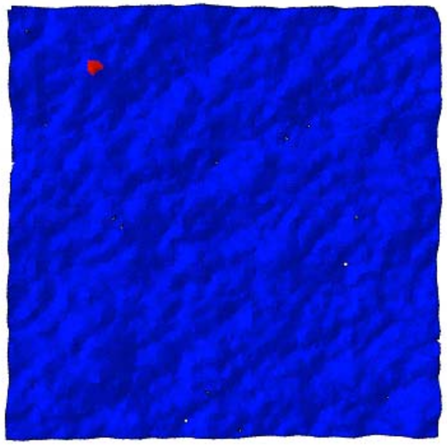
top surface, $rms = 50$ nm

Micro-scale: contact areas at low roughness

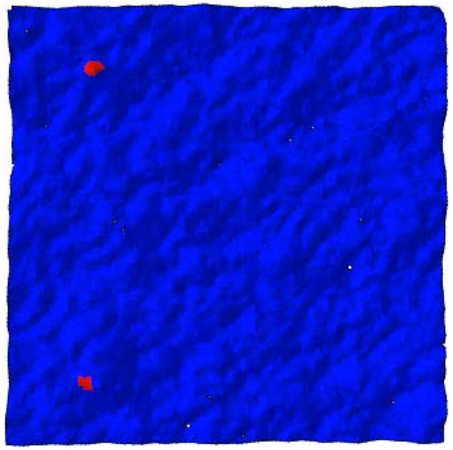

(a) $p < 0.0001$ MPa
(b) $p < 0.001$ MPa
(c) $p = 0.004$ MPa
(d) $p=0.605$ MPa
(e) $p=43$ MPa
(f) $p=1144$ MPa

Red region stands for area into contact.

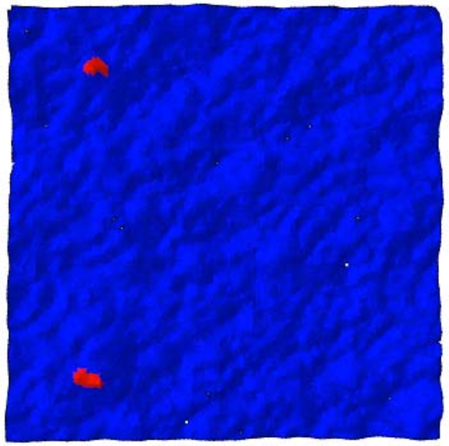
Micro-scale: contact areas at high roughness



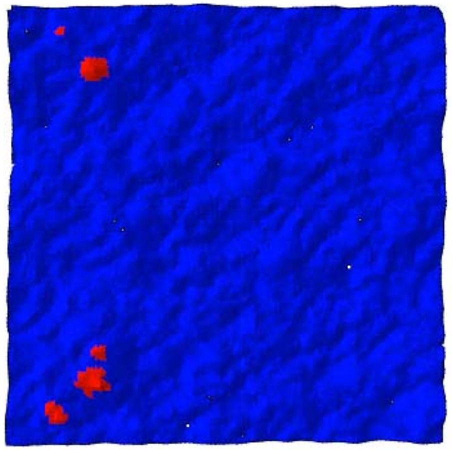
(a) $p < 1$ MPa



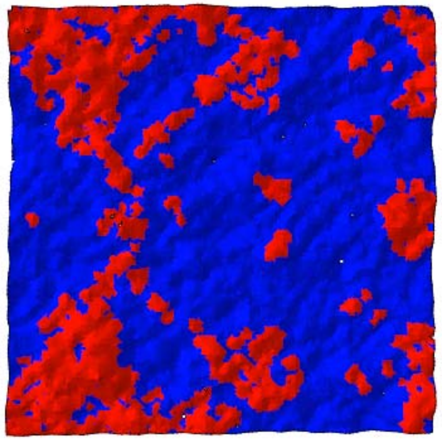
(b) $p <$ 2 MPa



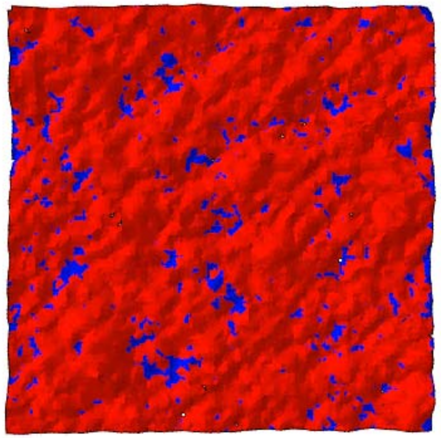
(c) p=10 MPa



(d) p=43 MPa



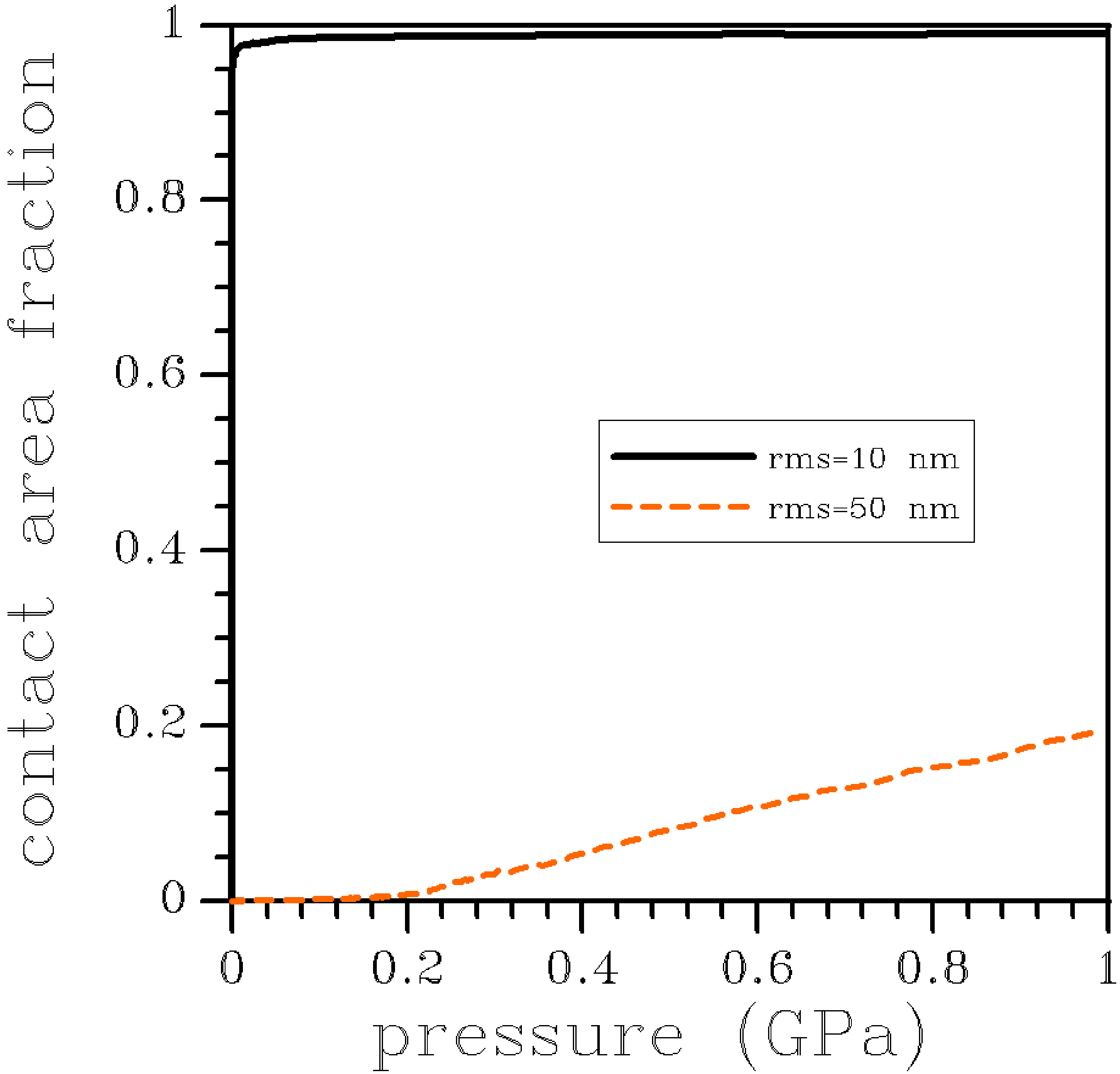
(e) $p \cong 4$ GPa



(f) $p \gg 4$ GPa

Red region stands for area into contact..

Micro-scale: contact area vs pressure



Clearly, assessing the surface roughness is pivotal to obtain a performing bond.

Conclusions and future work

A first attempt, three-scale, purely mechanical approach has been applied to the (thermo-)compressive bonding process.

The local pressure on the contact metal rings can be roughly estimated and some insights on the areas effectively entered into contact can be obtained.

This information could be linked to the effective bonding quality for the dices distributed on the wafer.

Future focus on:

- the micro-scale simulations, which appear too much time-consuming for a stochastic (e.g. Monte Carlo) analysis;
- experimental values of thin metal film properties, possibly far from the corresponding bulk properties;
- account for thermal coupling and recrystallization.