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Characterization of mechanical behavior of nanocrystalline layer induced by SMAT using micro-pillar compression technique coupled with finite element analysis

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Micro-pillar compression tests to characterize the mechanical behavior of different layers induced by SMAT in a 316L stainless steel.

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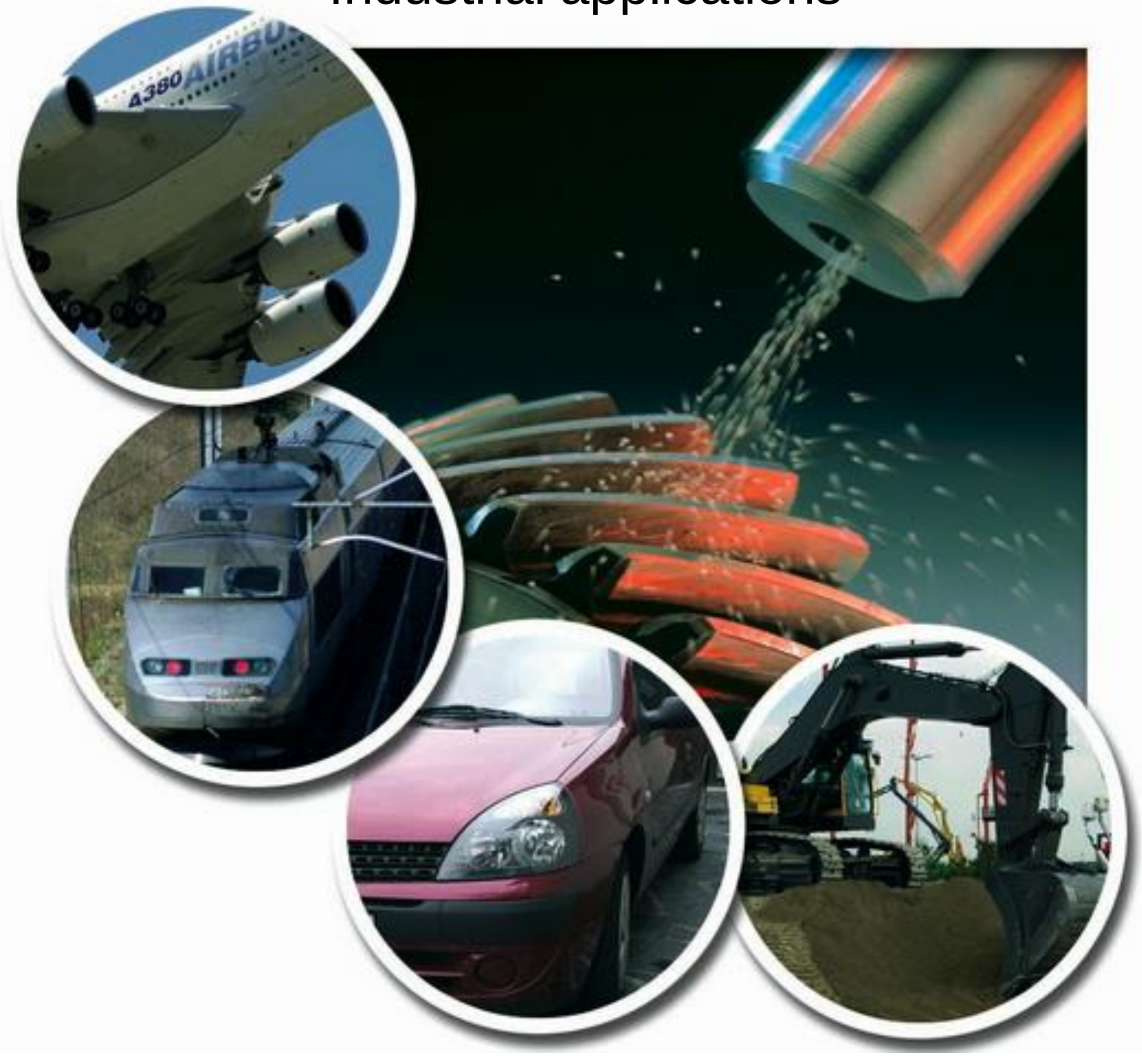
Summary

- Introduction
- Material and experimental conditions
- Results of micro-pillar compression
- Numerical simulations of micro-pillar compression
- Conclusions and prospects

Introduction: shot peening

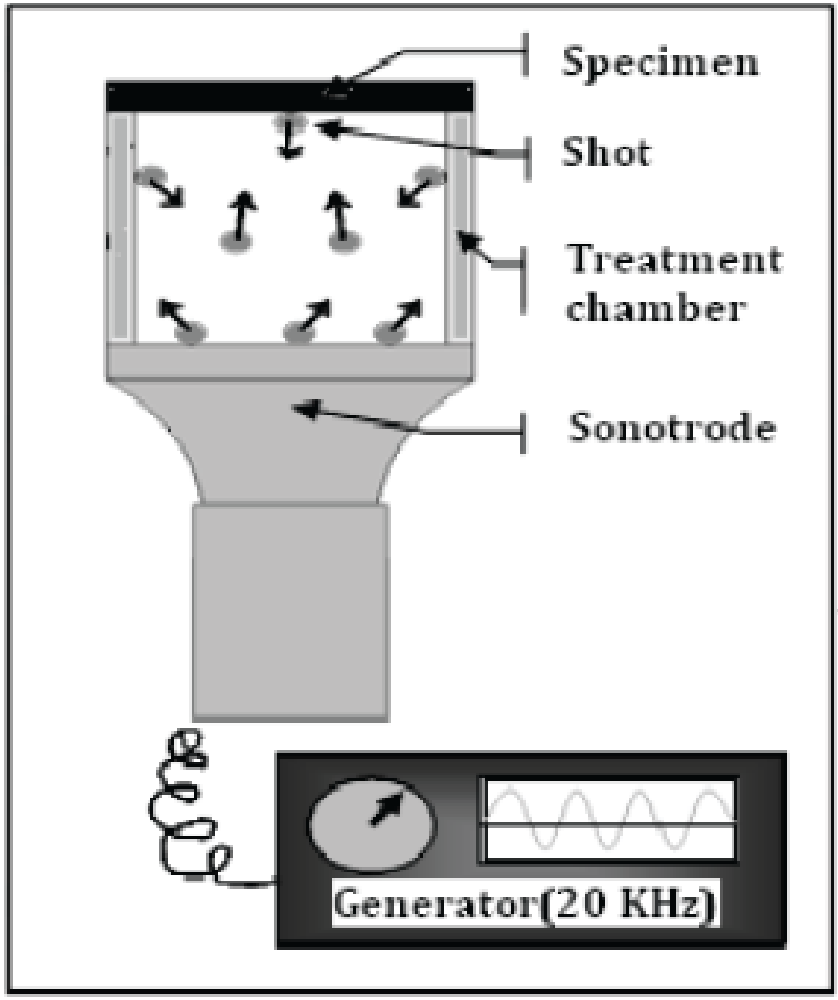
Industrial applications

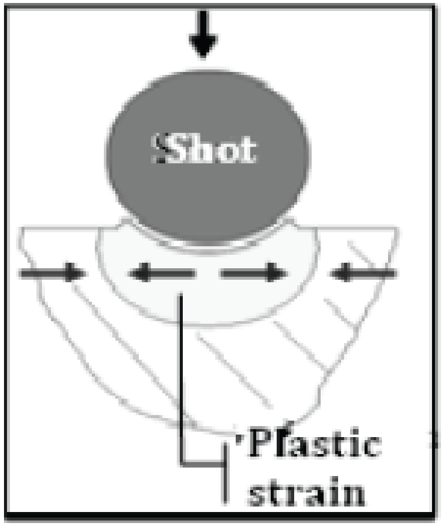


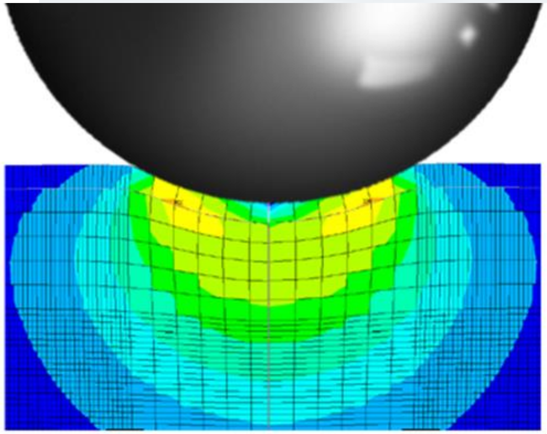
Variants of shot peening:

- Ultrasonic shot peening (USSP)
- **Surface mechanical attrition treatment (SMAT)**
- High-energy shot peeing (HESP)
- Surface nanocrystallization and hardening (SNH)
- Particle impact processing (PIP)

Introduction : SMAT



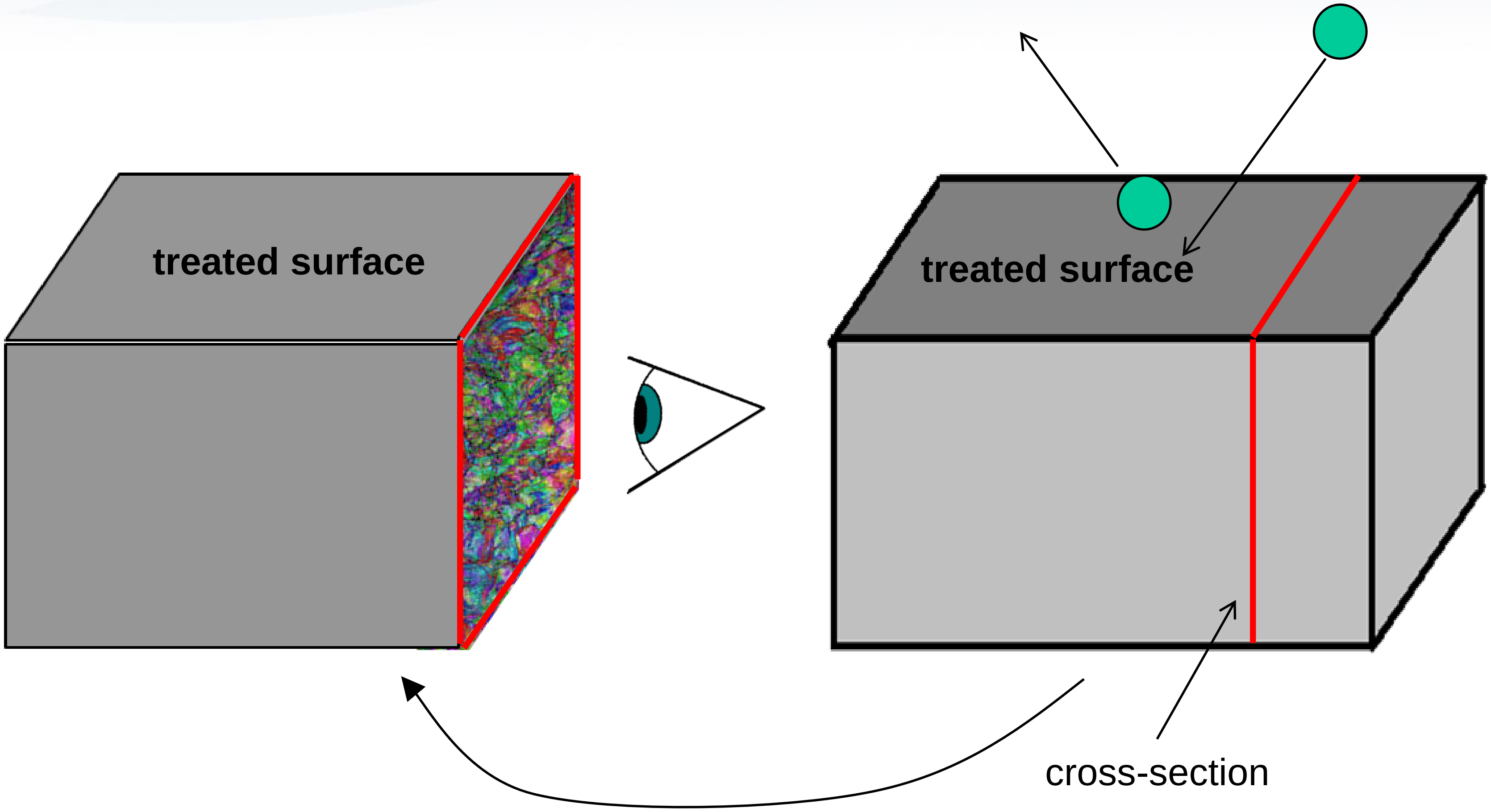




SMAT : (Surface Mechanical Attribution Treatment)

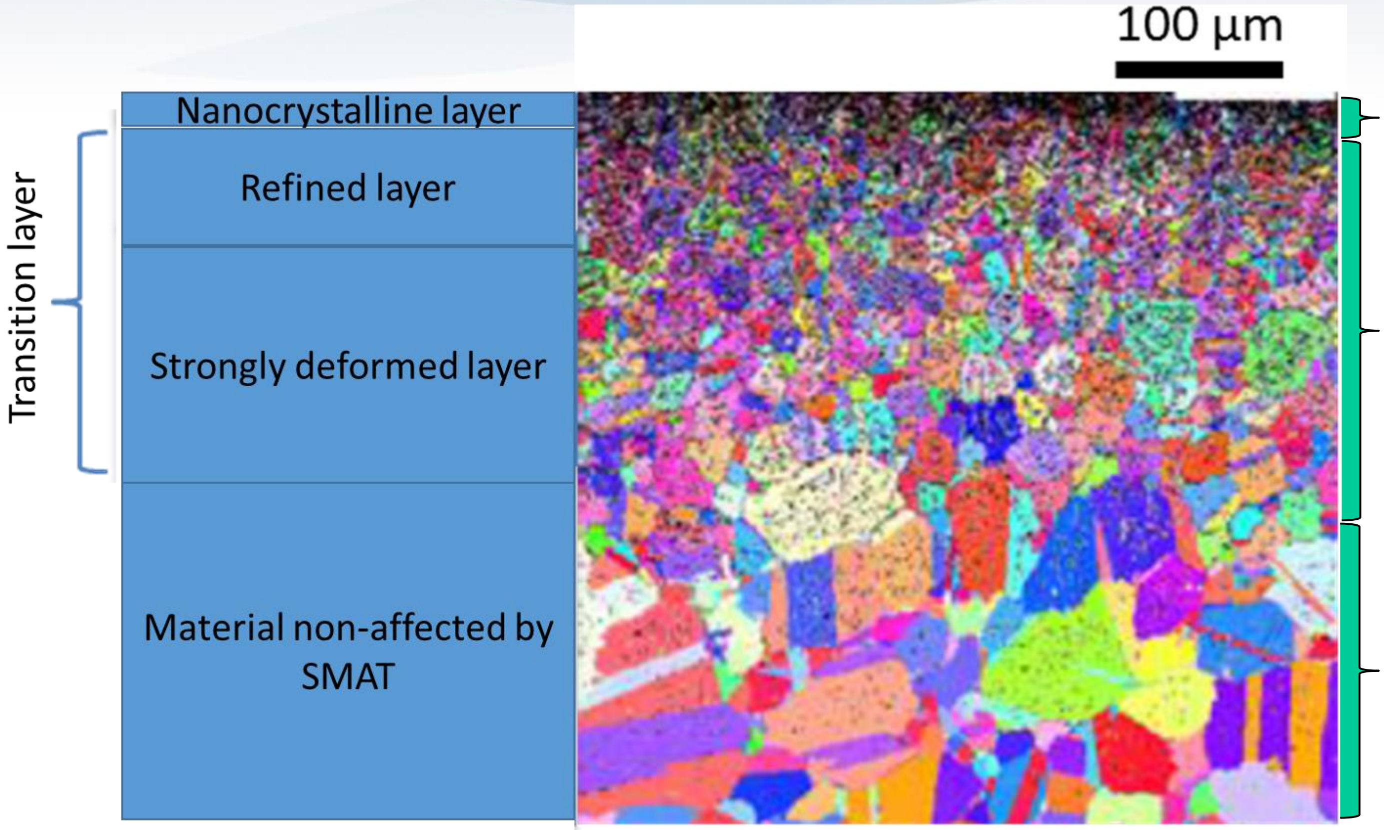
SMAT is able to nanocrystallize the surface of the material due to the severe plastic deformation generated at a high deformation rate.

Introduction : SMAT



Introduction : SMAT

Layers obtained after SMAT :



Grain size: nanometer scale
Thickness: 10~50 µm

Grain size:
From nanometer scale
to micrometer scale

Grain size: micrometer scale

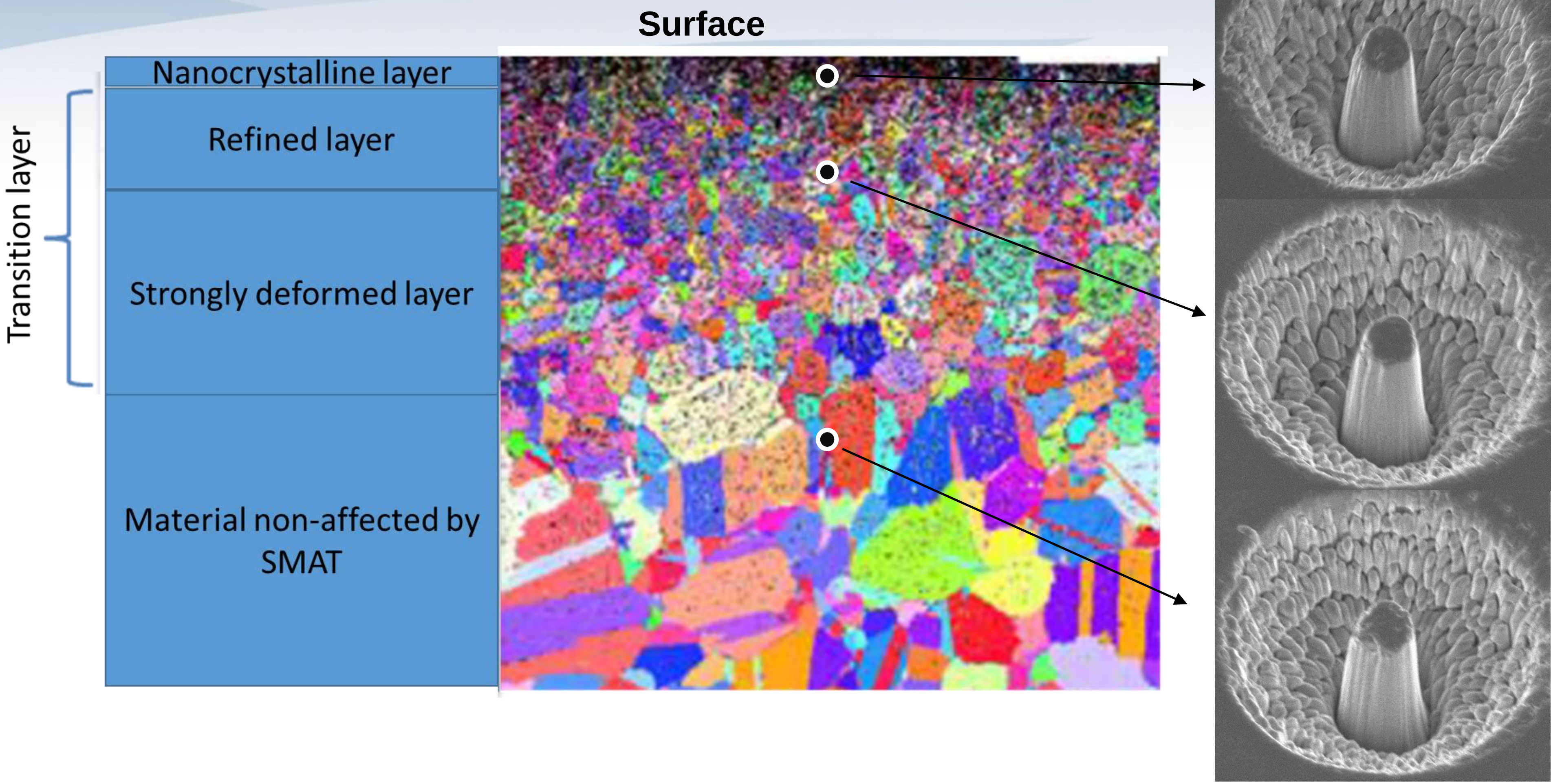
Introduction : Micro-pillar compression tests

- **How to characterize the mechanical behavior of different layers?**

↓

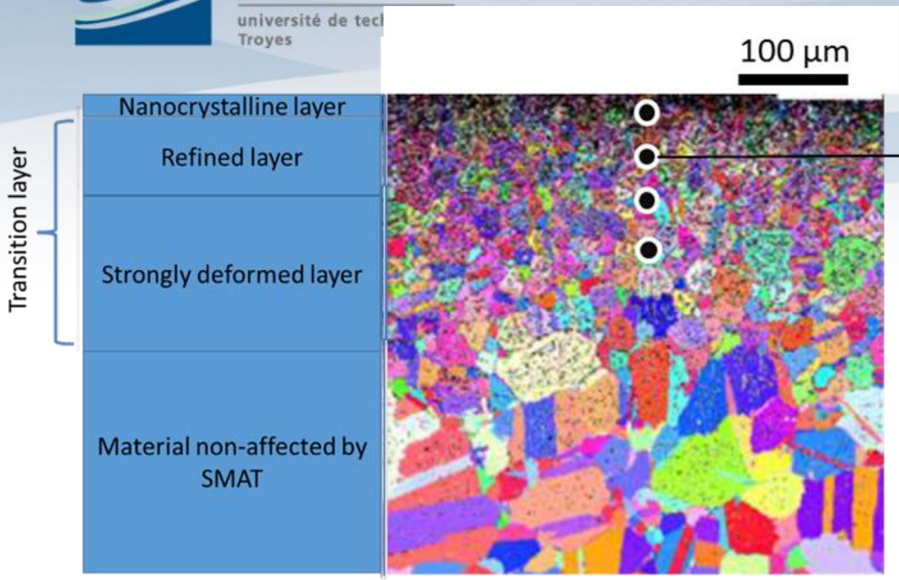
Micro-pillar compression → **Test at micrometer scale**

Introduction : Micro-pillar compression tests

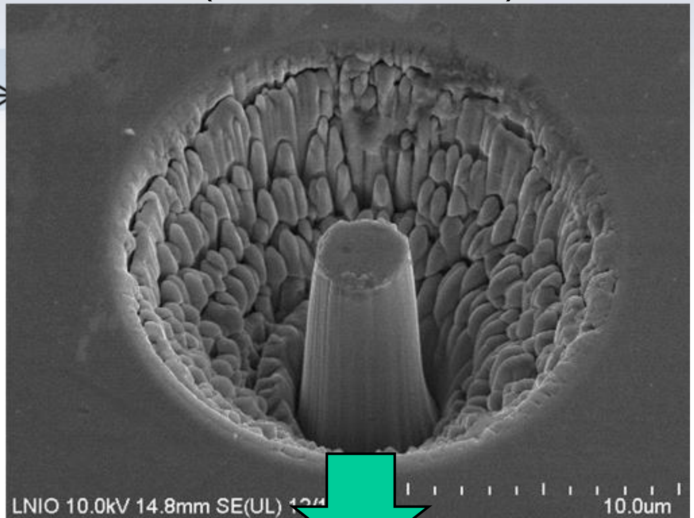


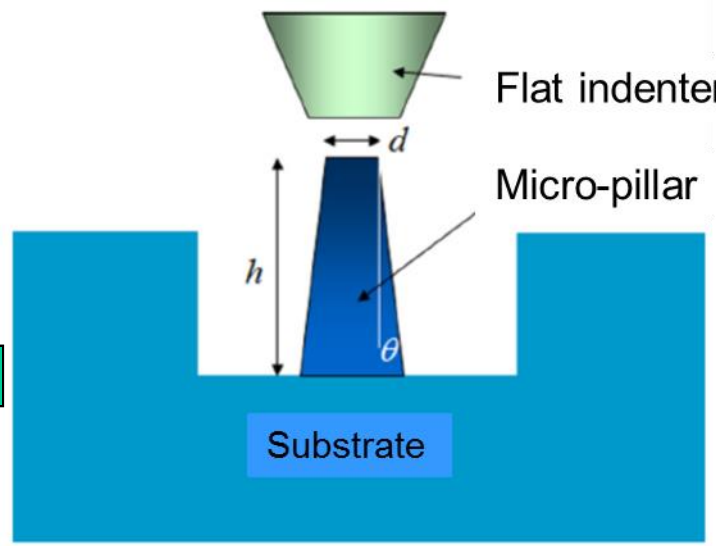
Micro-pillar machined by FIB (focused ion beam) at different depths.

Introduction : Micro-pillar compression tests



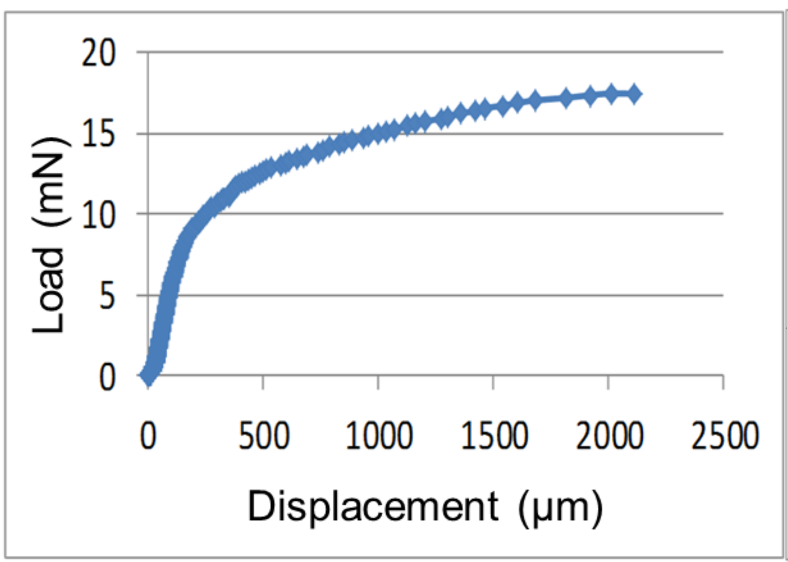
«Machining » of micro-pillars with FIB (focused ion beam)





Compression carried out with a Nanoindenter(with a flat head)

Load-displacement curve



Material and experimental conditions

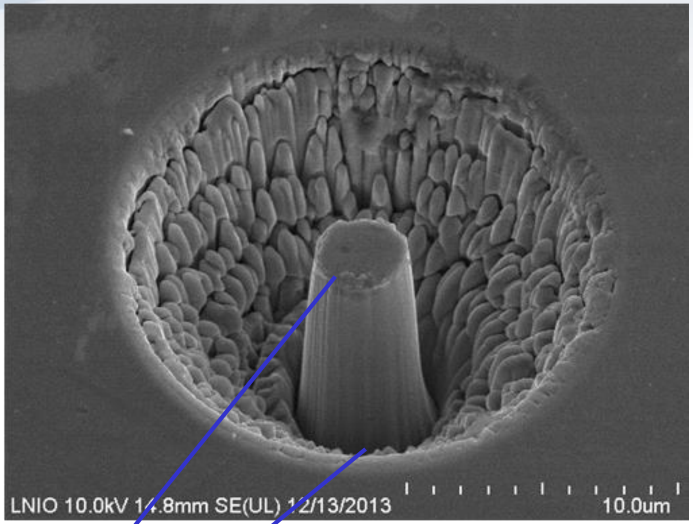
- Material: 316L stainless steel.

- SMAT treatment:
  - Frequency: 20 kHz
  - Diameter of impact balls: 3 mm
  - Duration: 30 min

- Micro-pillars compression test.
  - Nanoindenter with a flat head
  - Deformation rate: 0.05 s^{-1}
  - Micro-pillar with a taper angle

    Upper/lower diameter: 2 µm and 4 µm

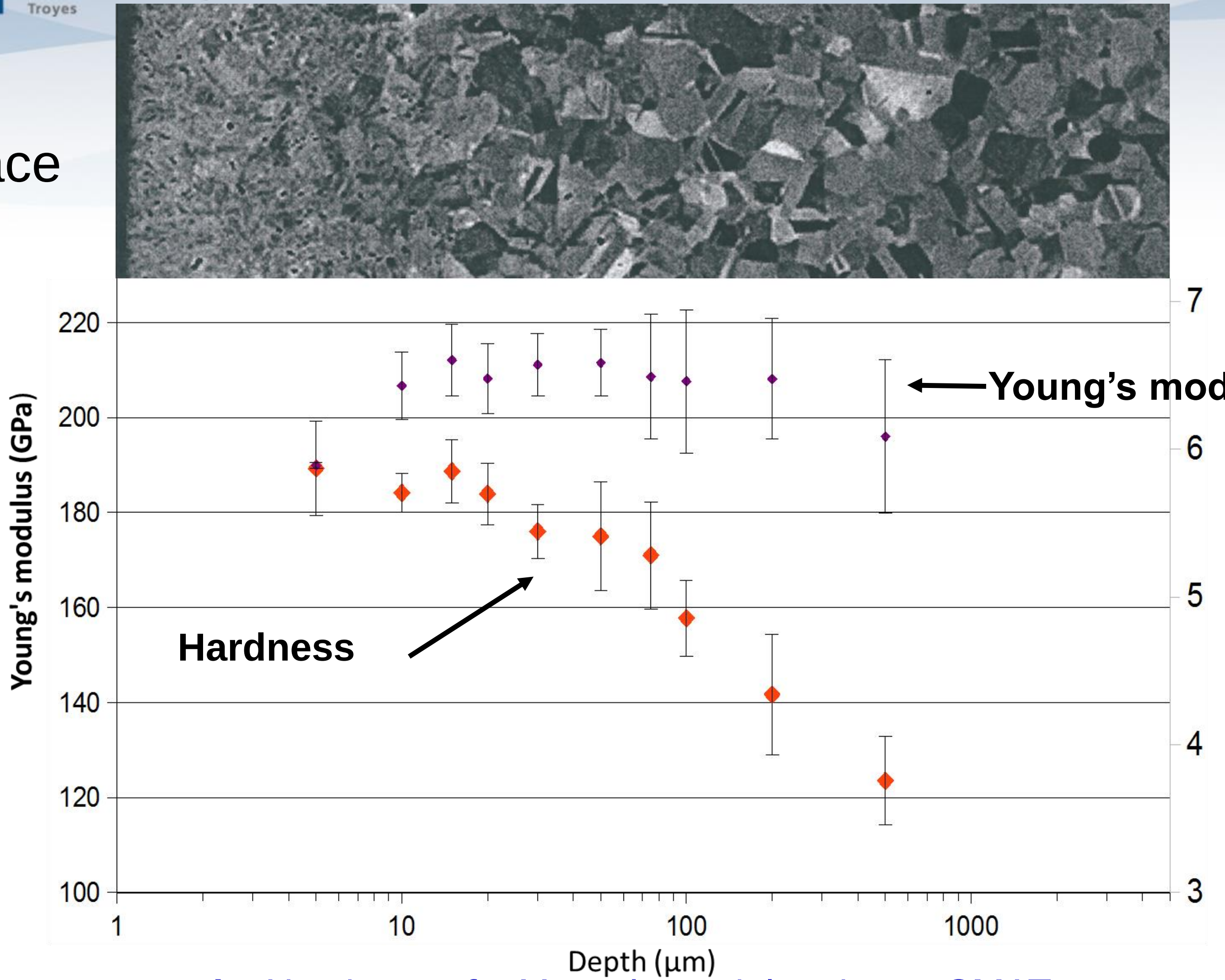
    Height: 10 µm



Result: Hardness and Young's modulus

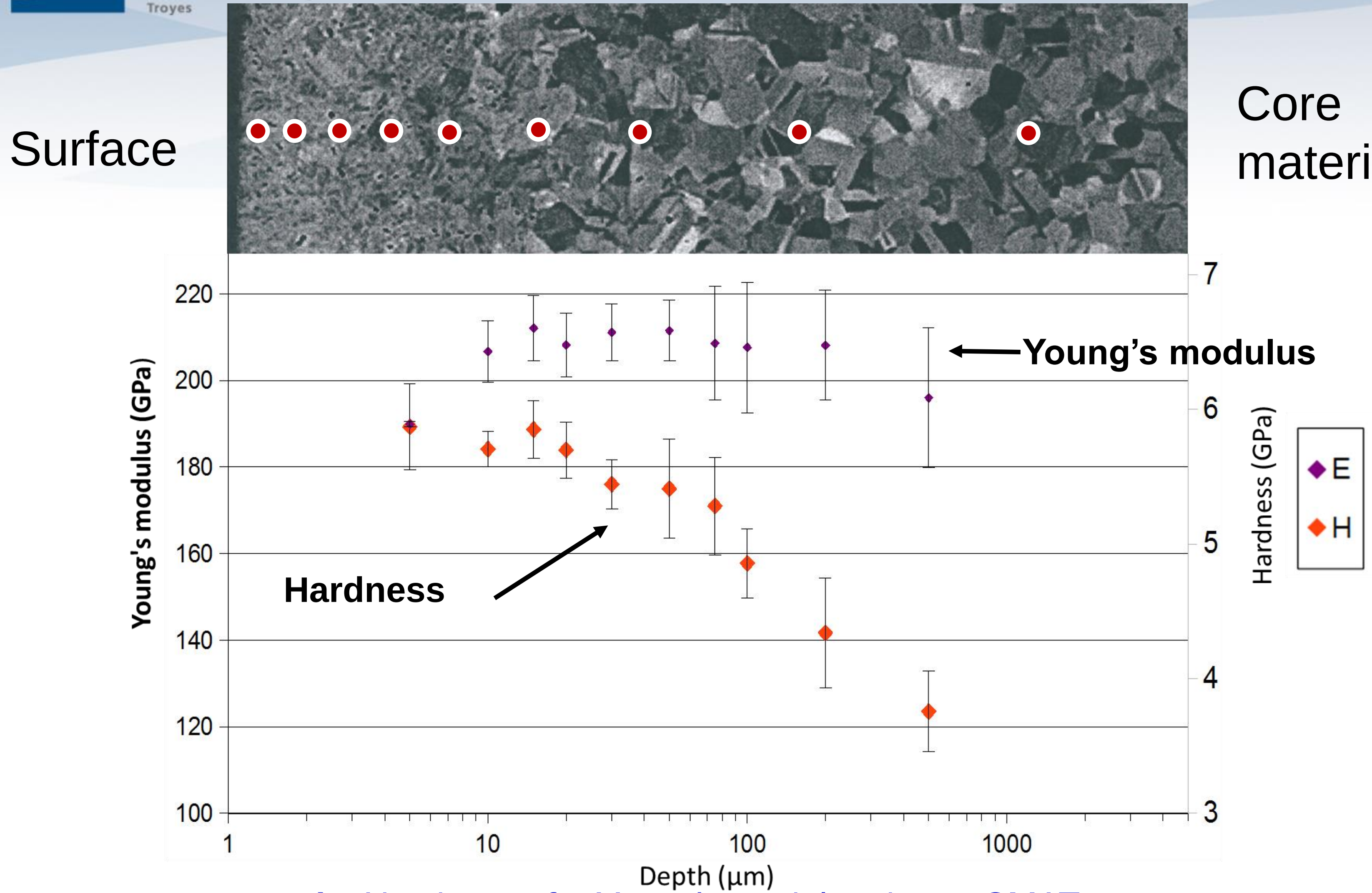
Surface

Core material



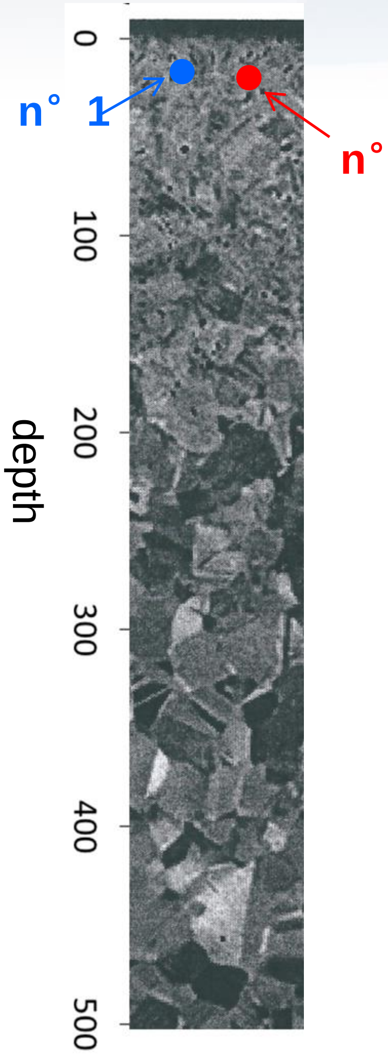
→ No change for Young's modulus due to SMAT
→ Significant increase of hardness near the surface
→ Depth affected by SMAT at least 300 µm

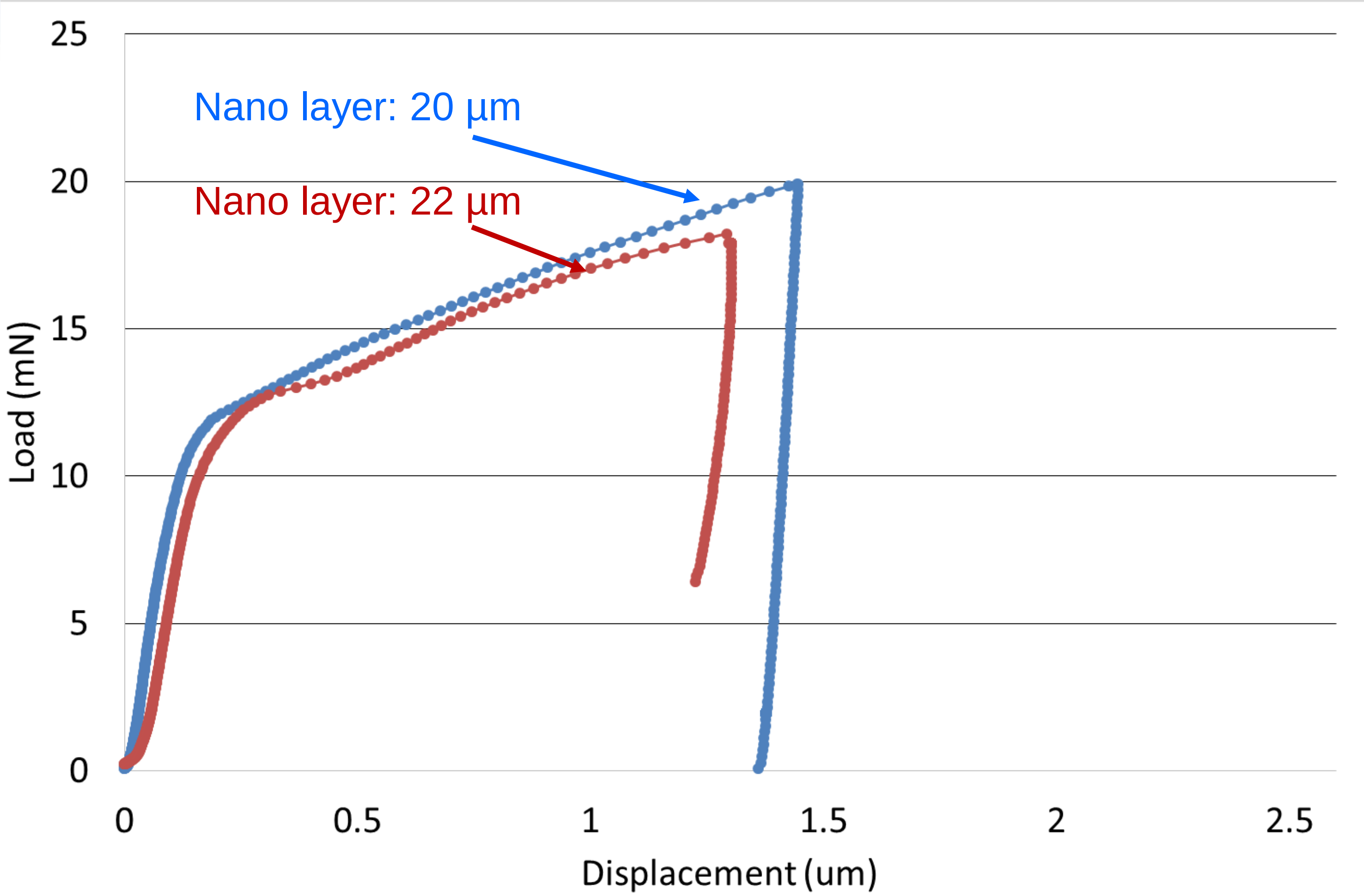
Result: Hardness and Young's modulus



- → No change for Young's modulus due to SMAT
- → Significant increase of hardness near the surface
- → Depth affected by SMAT at least 300 µm

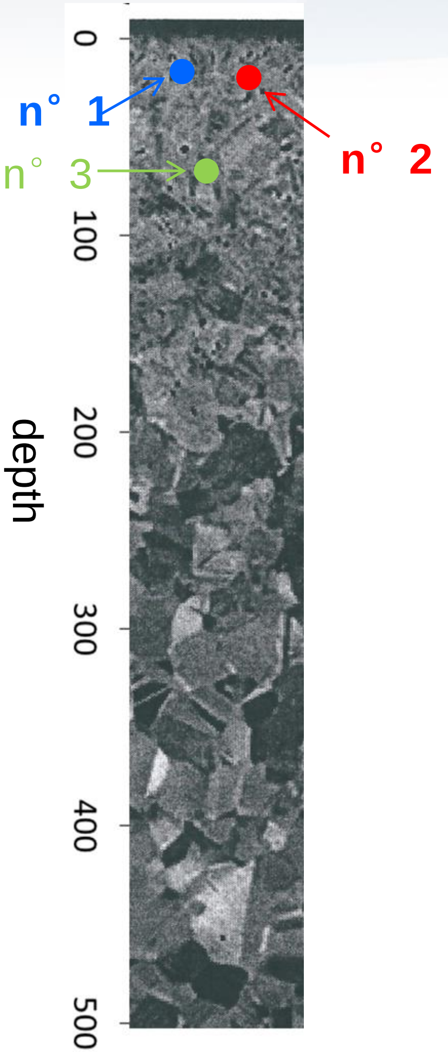
- Load-displacement curves:

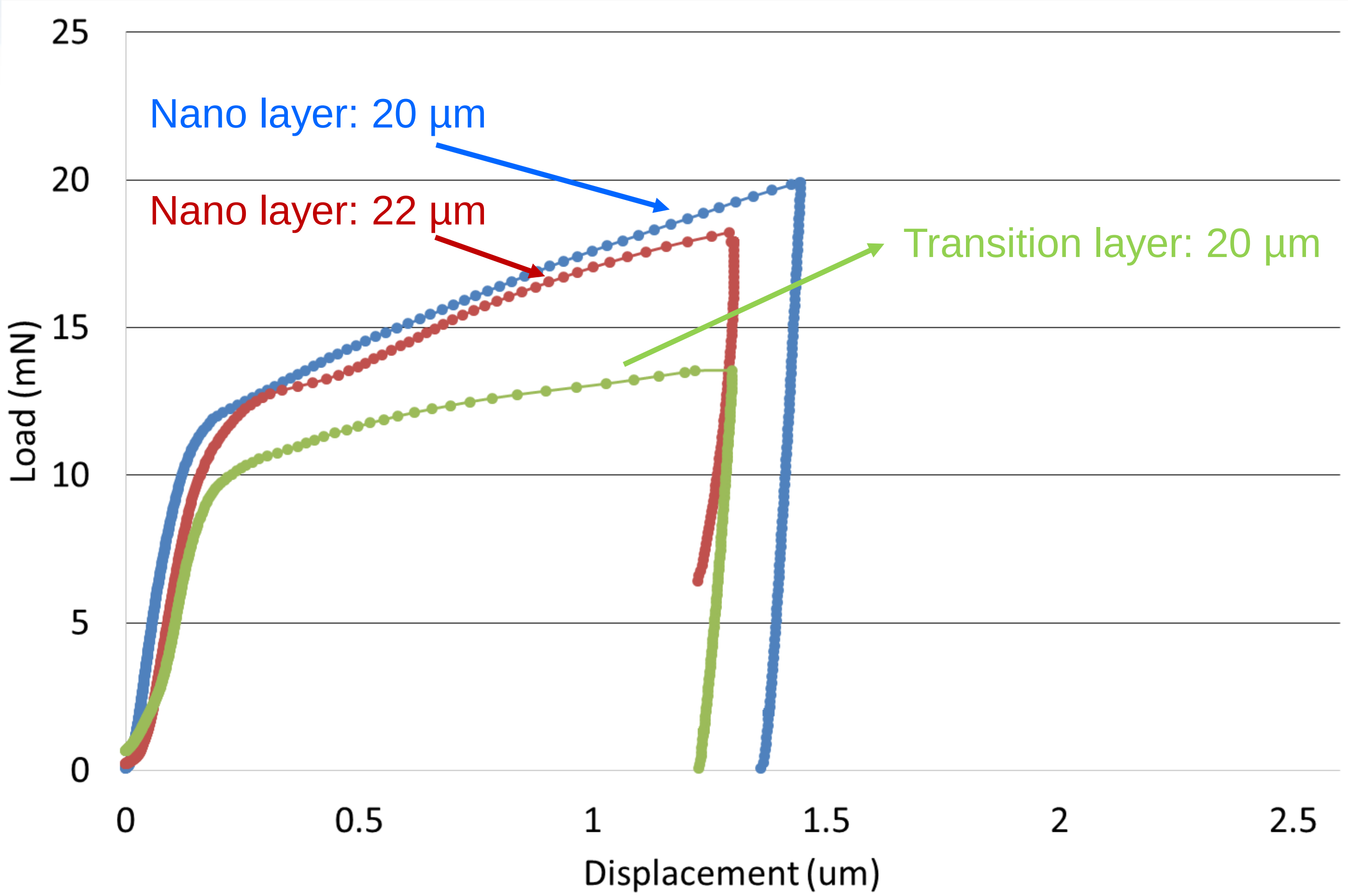




Result : Micro-pillar compression

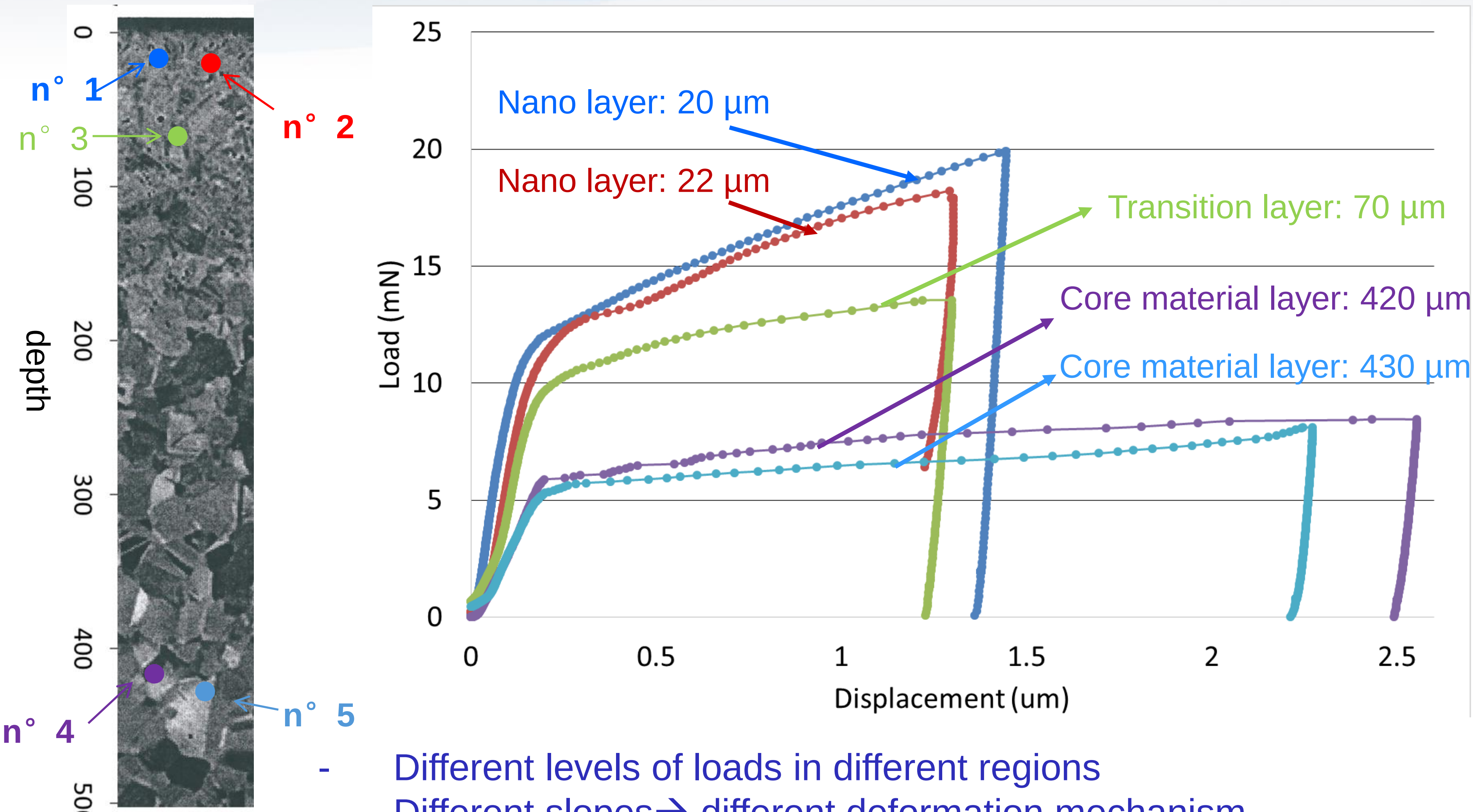
- Load-displacement curves:





Result : Micro-pillar compression

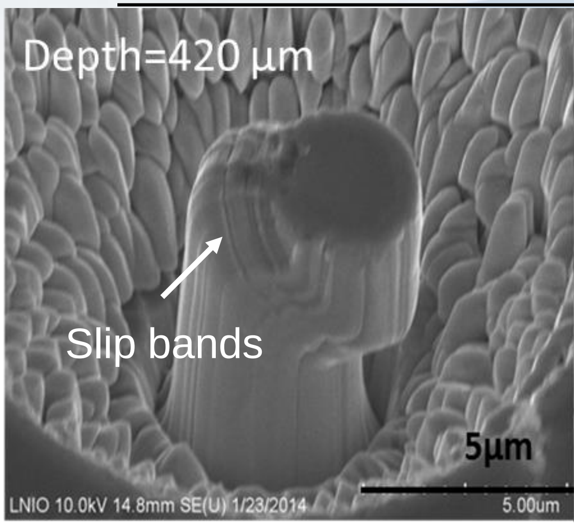
- Load-displacement curves:



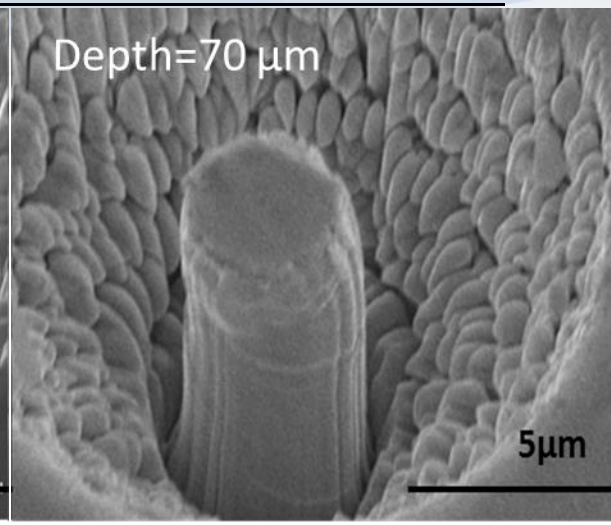
- Different levels of loads in different regions
- Different slopes→ different deformation mechanism

Results: Micro-pillar compression

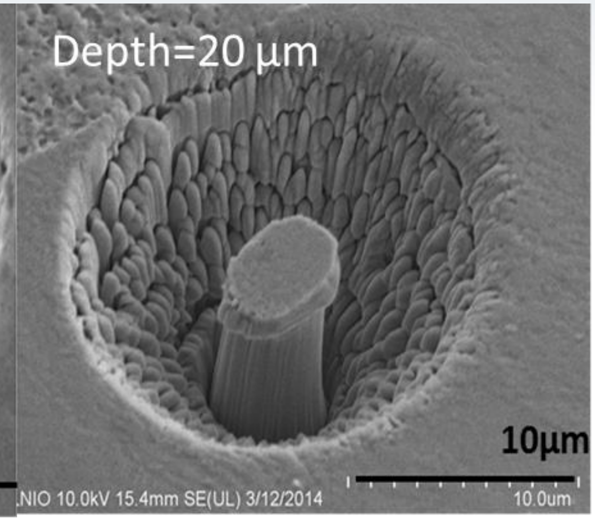
- Observation of deformed state:



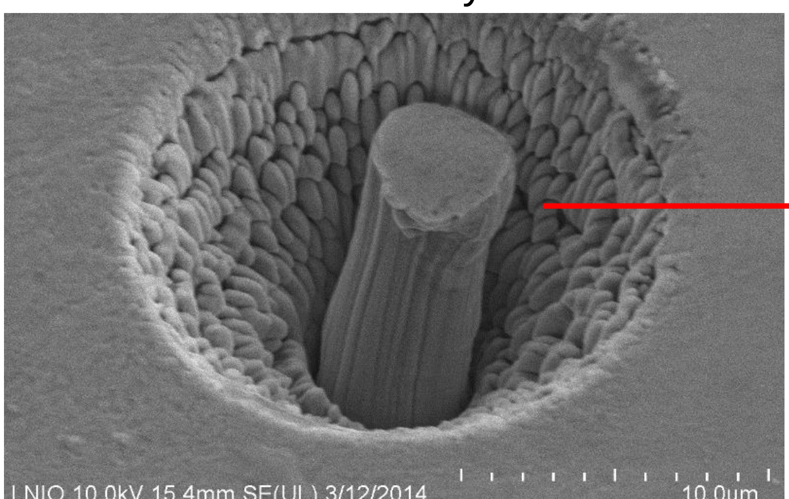
Core material:
Zones non-affected by SMAT



Transition layer



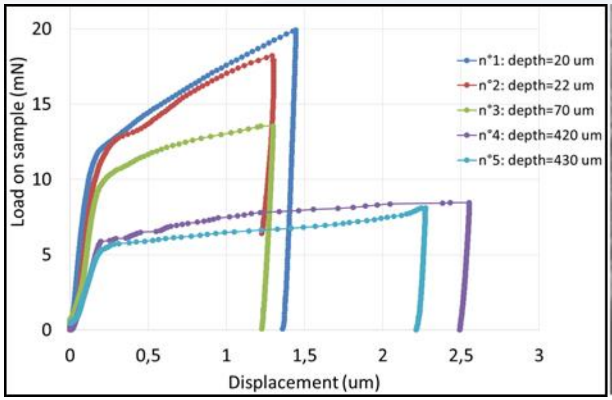
Nanostructured layer:
Zones with nano-grains

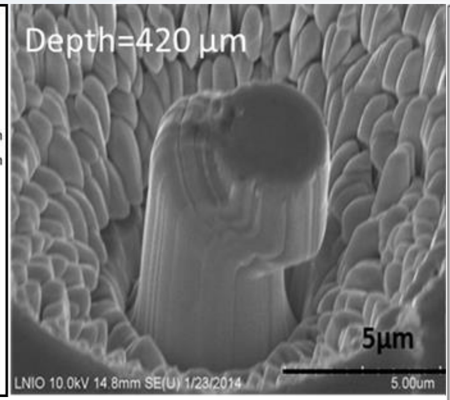


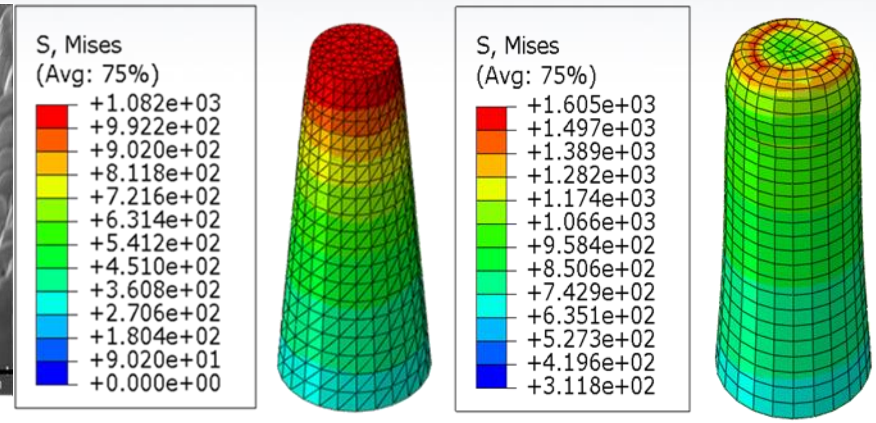
Deviation of micro-pillar: possible cause could be misalignment.

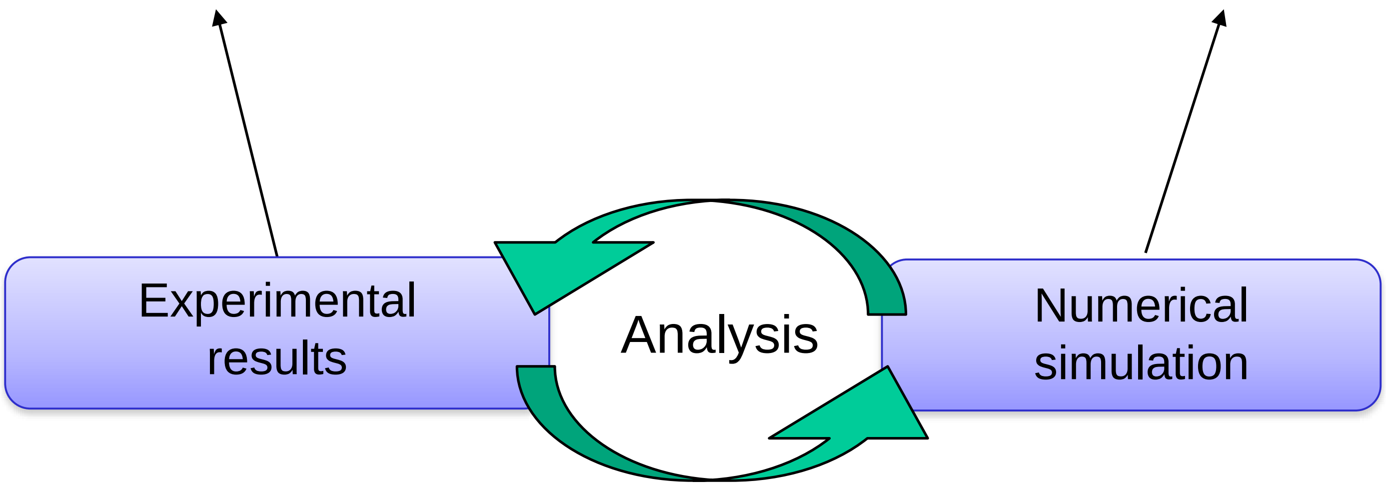
Numerical simulation

Numerical simulation on micro-pillar compression:









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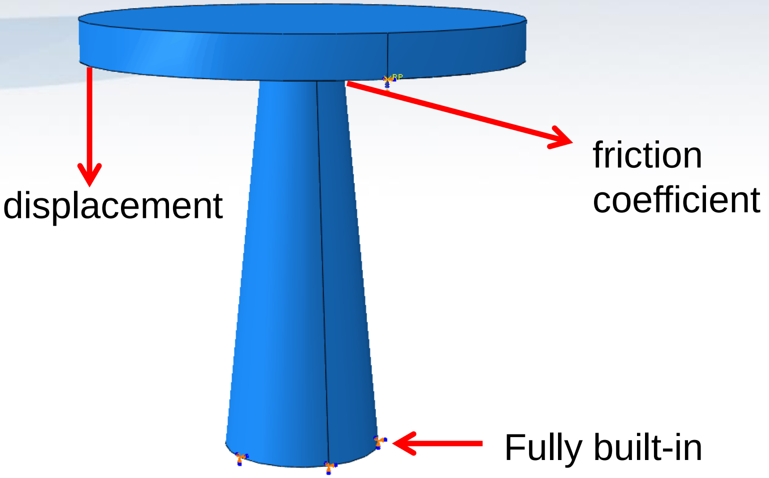
Numerical simulation

Simulation conditions:



-Material :
Steel - pillar(E=210GPa ν=0.3)
Diamond - indenter (E=1141GPa ν=0.07)

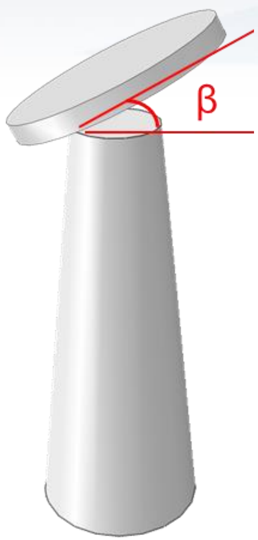
-Friction coefficient: 0.15

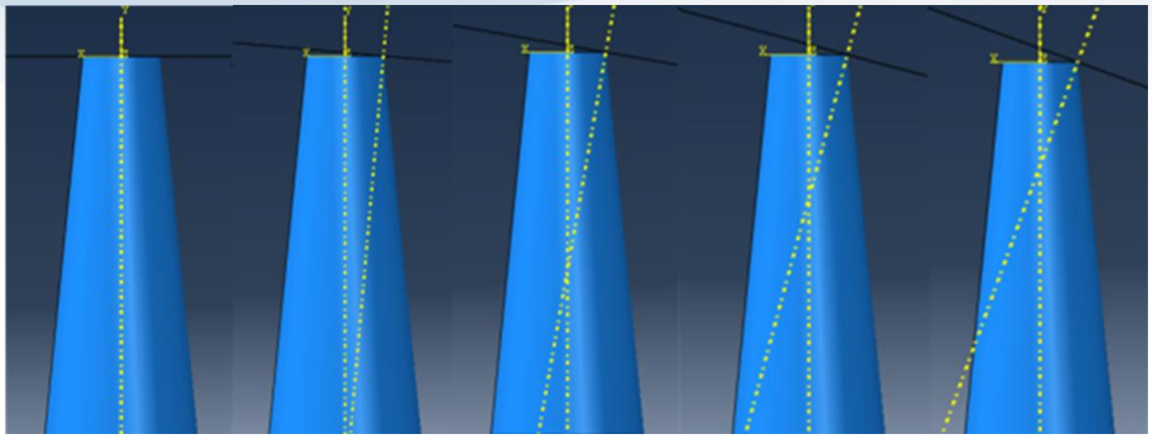
-Displacement: 20% of the initial height

-The lower surface is fully built-in.

Studied parameters → Misalignment / Strain hardening → Significant influence

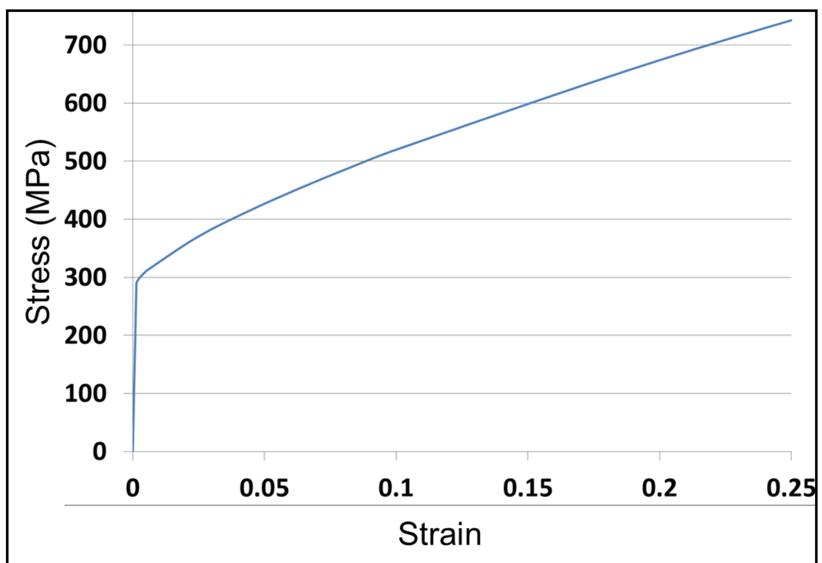
Influence of misalignment:





0° 5° 10° 15° 20°

Misalignment



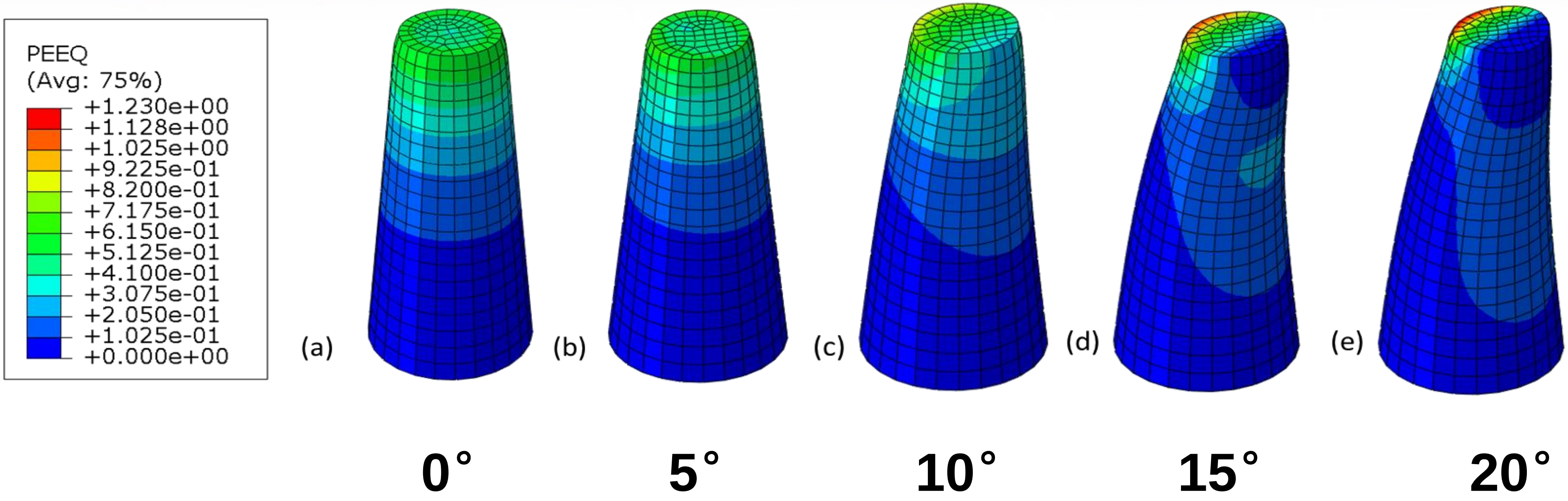
-Constitutive behavior :

$$\sigma = 290 + 1255\varepsilon_p^{0.733}$$

J. Petit, Materials Science and Engineering: 2012

Numerical simulation

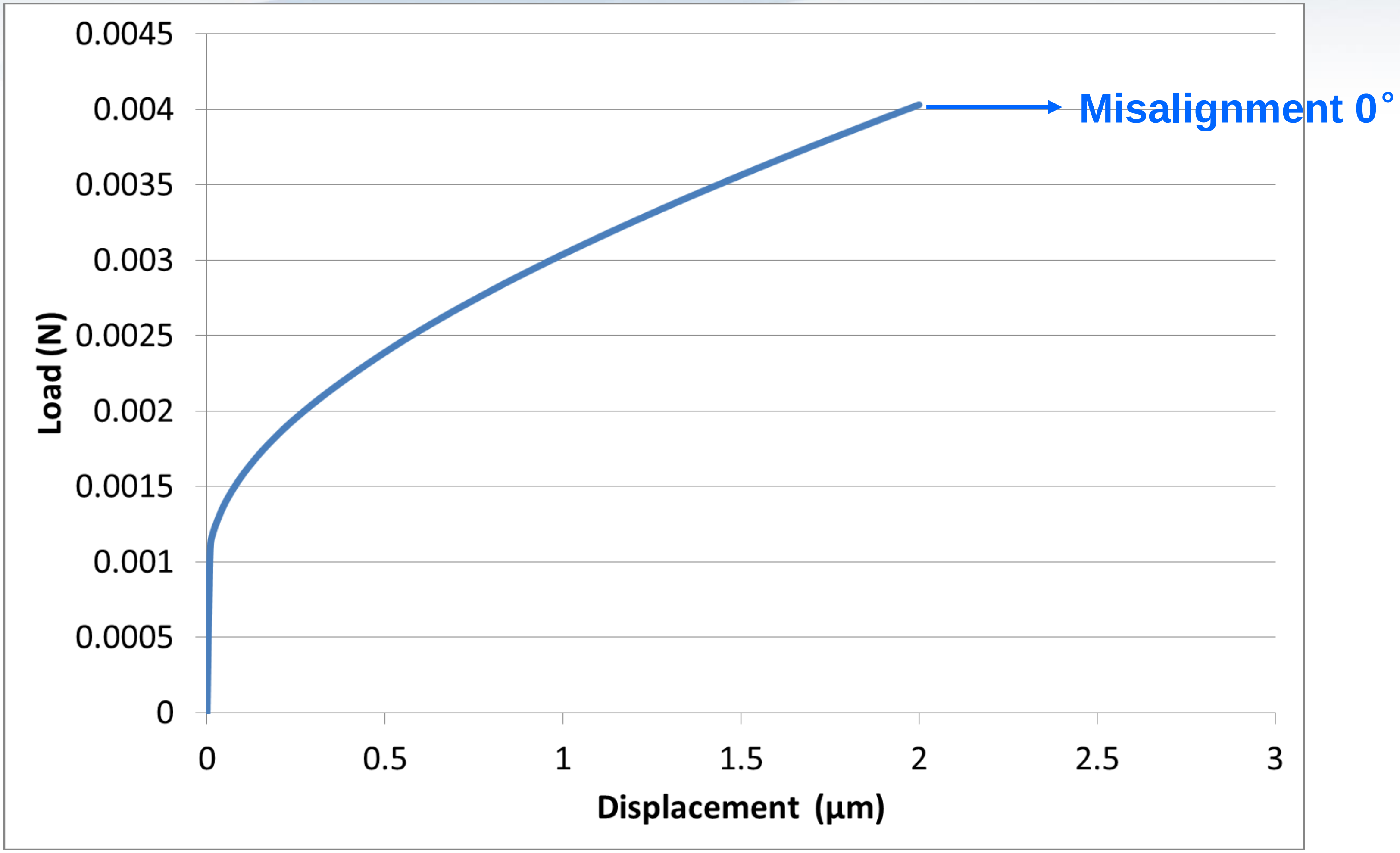
- <u>Strain field:</u>



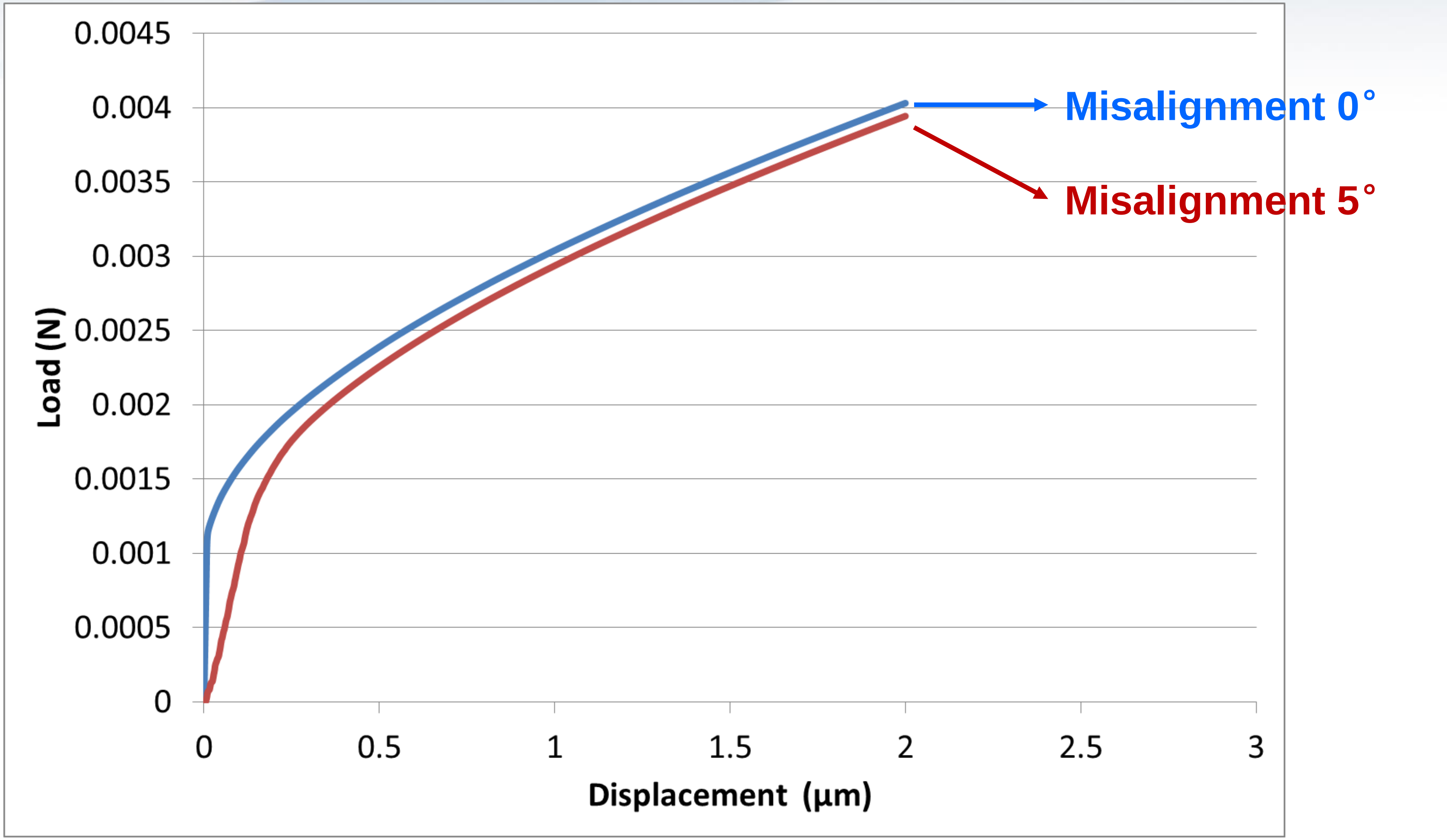
Equivalent plastic strain field

Numerical simulation

- Load-displacement curves:

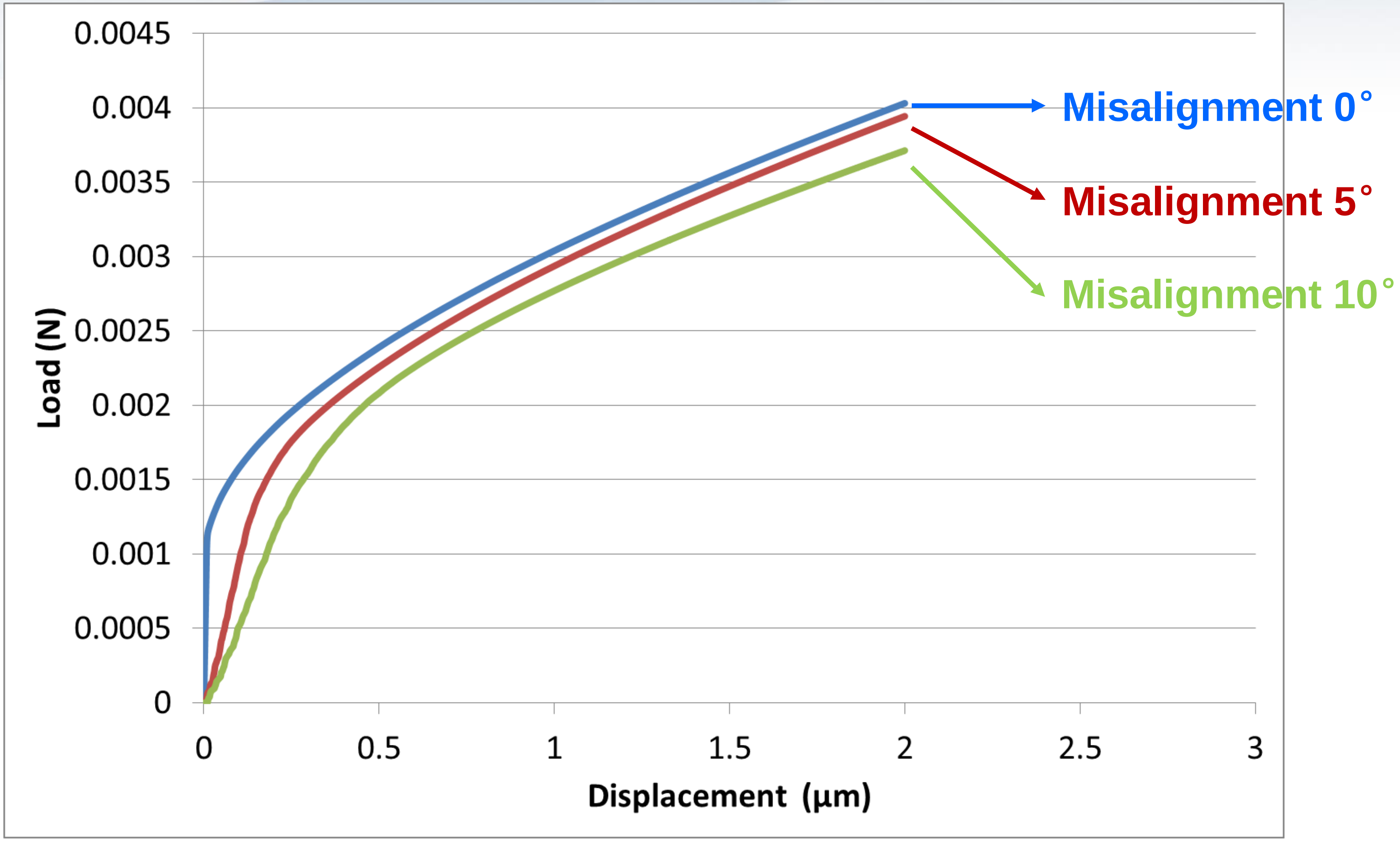


- Load-displacement curves:

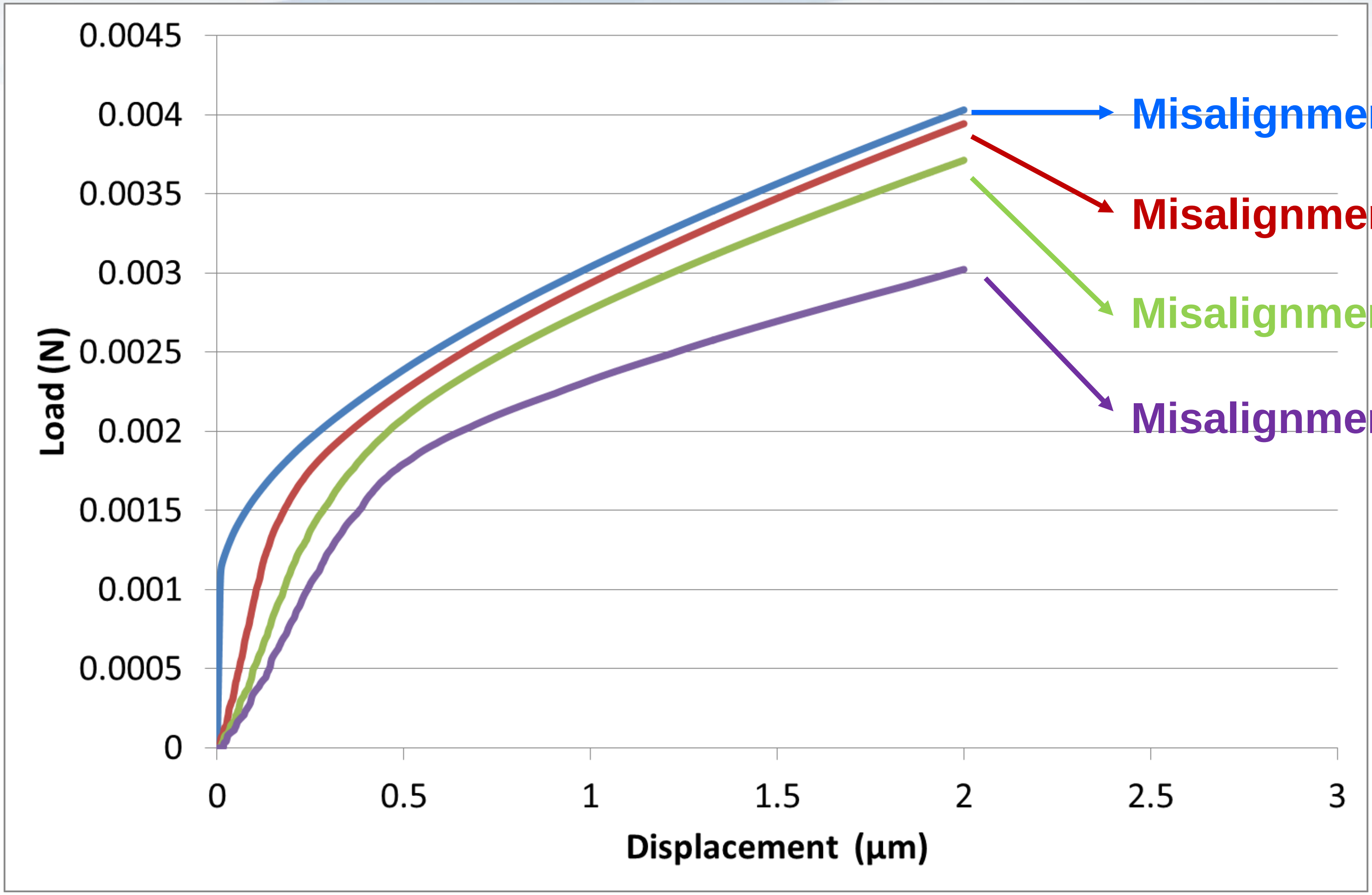


Numerical simulation

- <u>Load-displacement curves:</u>

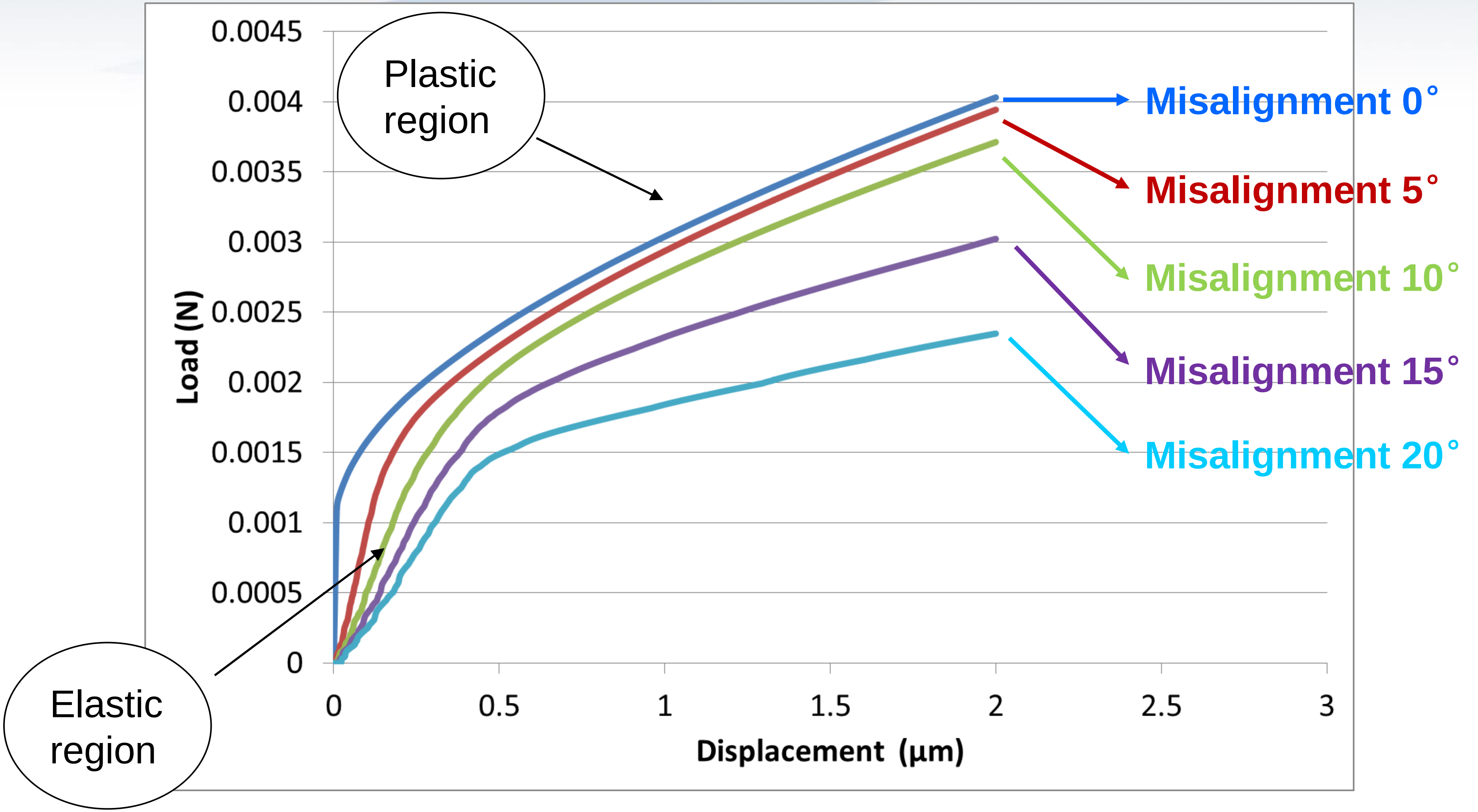


- Load-displacement curves:



Numerical simulation

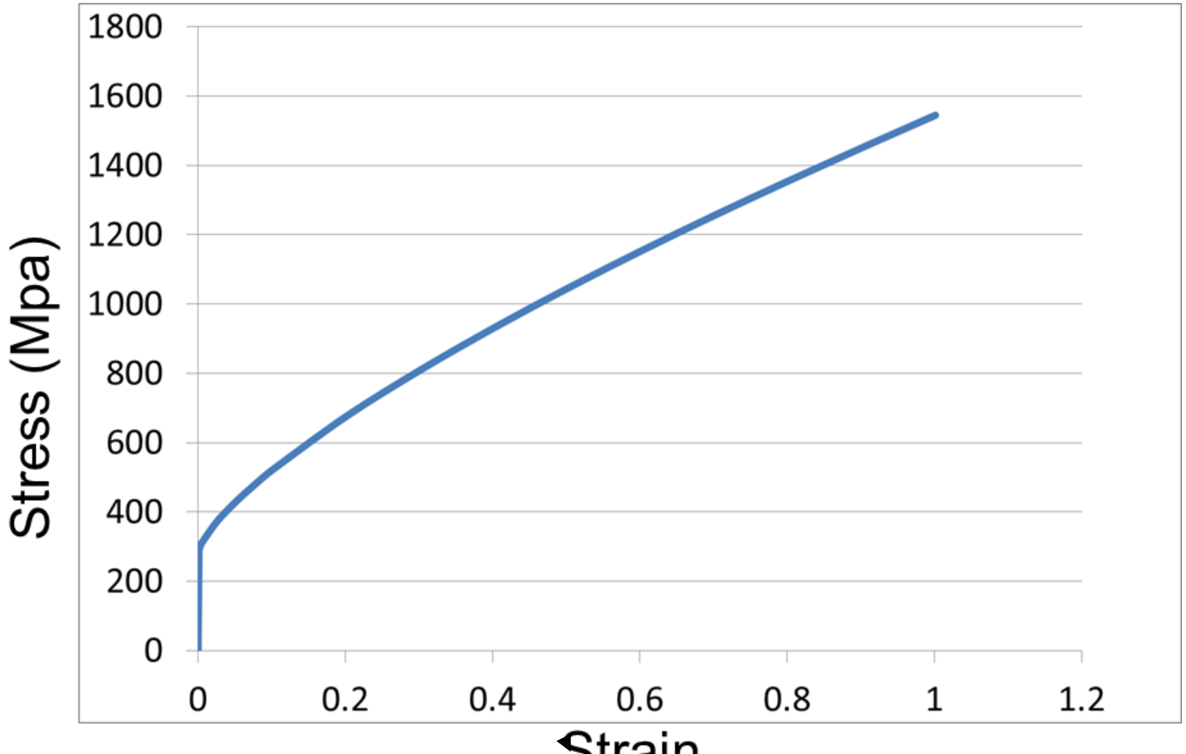
- <u>Load-displacement curves:</u>



- Decrease of the level of the load
- Decrease of slope in the elastic region and plastic region

- Simulation with different strain hardening coeficients:

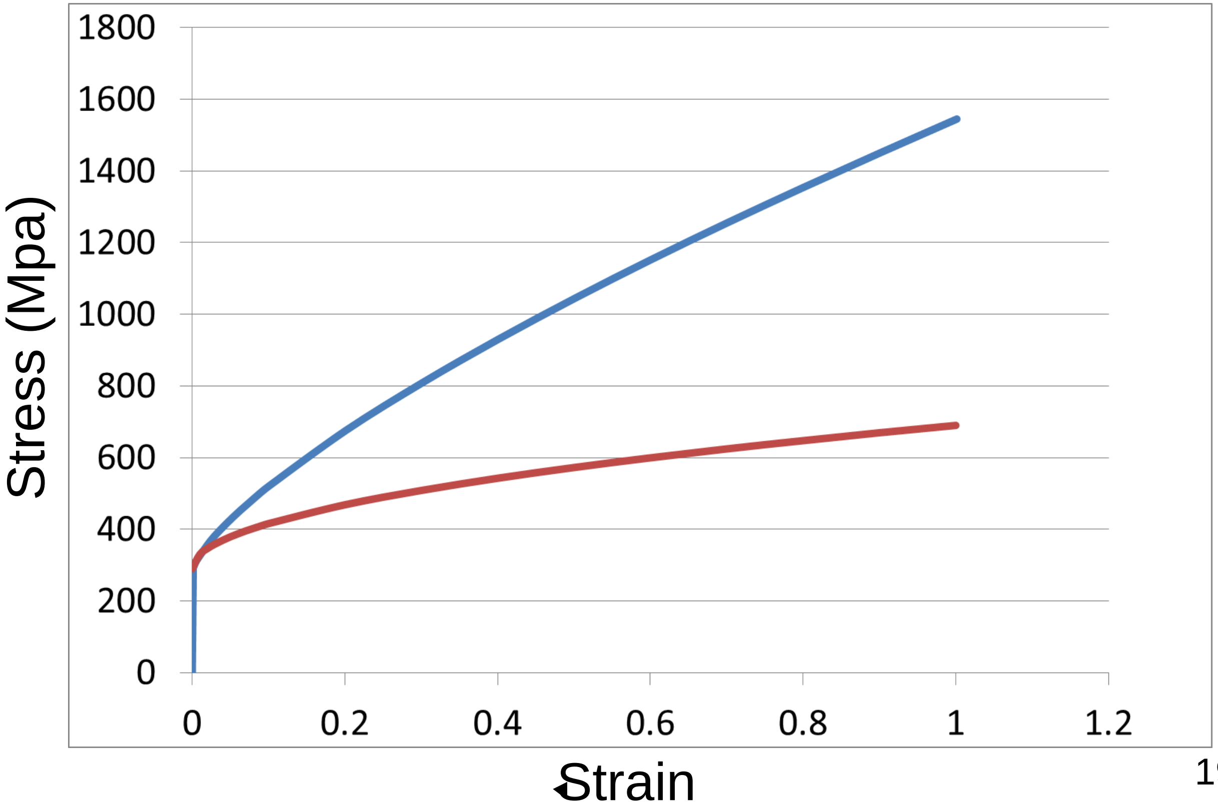
$$\sigma = 290 + 1255\varepsilon_p^{0.733}$$ → High strain hardening



Simulation on different deformation mechanisms :

$\sigma = 290 + 1255\varepsilon_p^{0.733}$ → High strain hardening

$\sigma = 290 + 400\varepsilon_p^{0.502}$ → Intermediate strain hardening



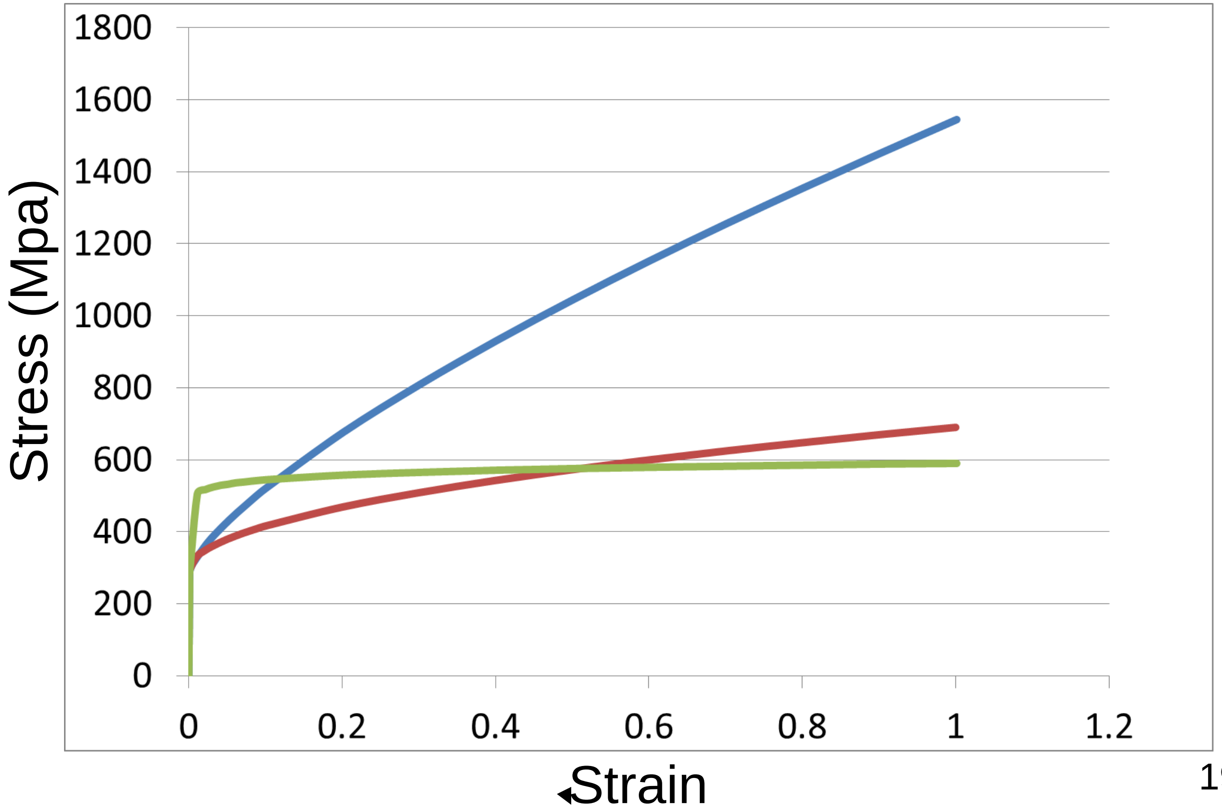
Simulation on different deformation mechanisms :

$$\sigma = 290 + 1255\varepsilon_p^{0.733}$$ → High strain hardening

$$\sigma = 290 + 400\varepsilon_p^{0.502}$$ → Intermediate strain hardening

$$\sigma = 290 + 300\varepsilon_p^{0.0712}$$ → Low strain hardening

Different levels of strain hardening.



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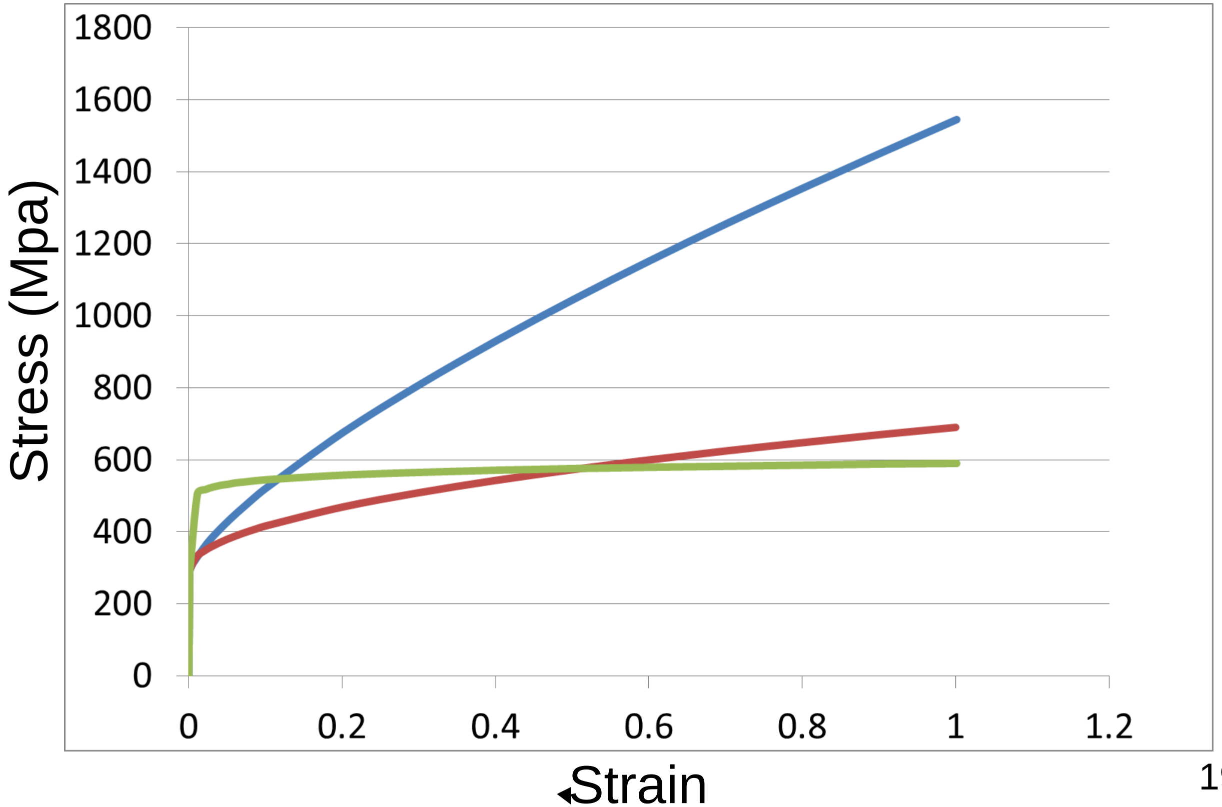
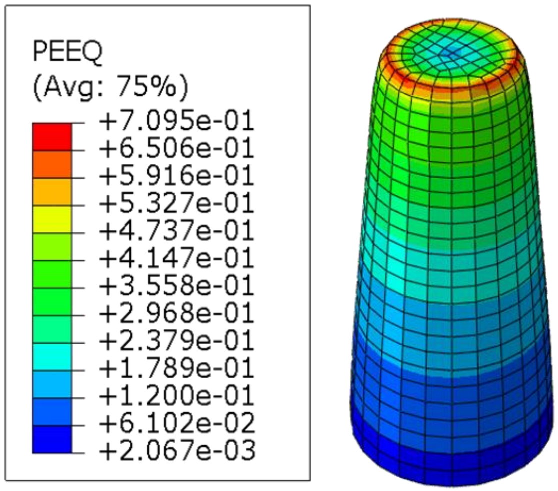
The same yield stress.

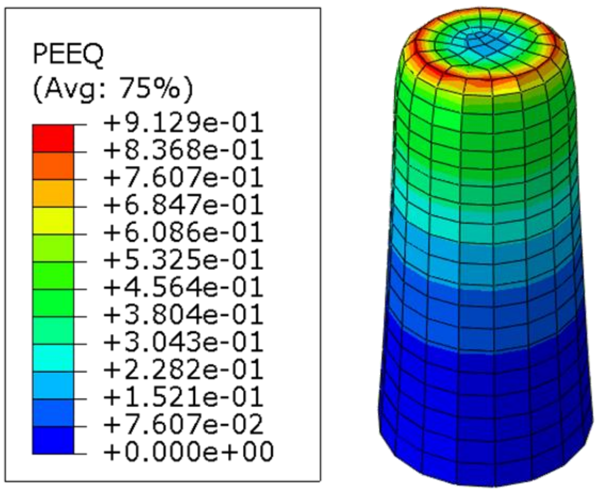
Different levels of strain hardening.



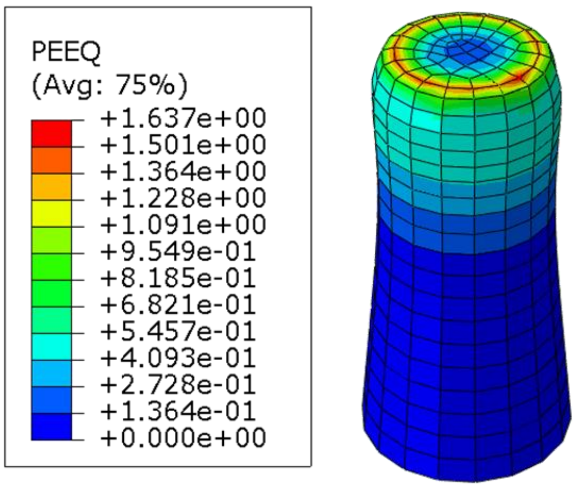
- <u>Strain field:</u>



High strain hardening



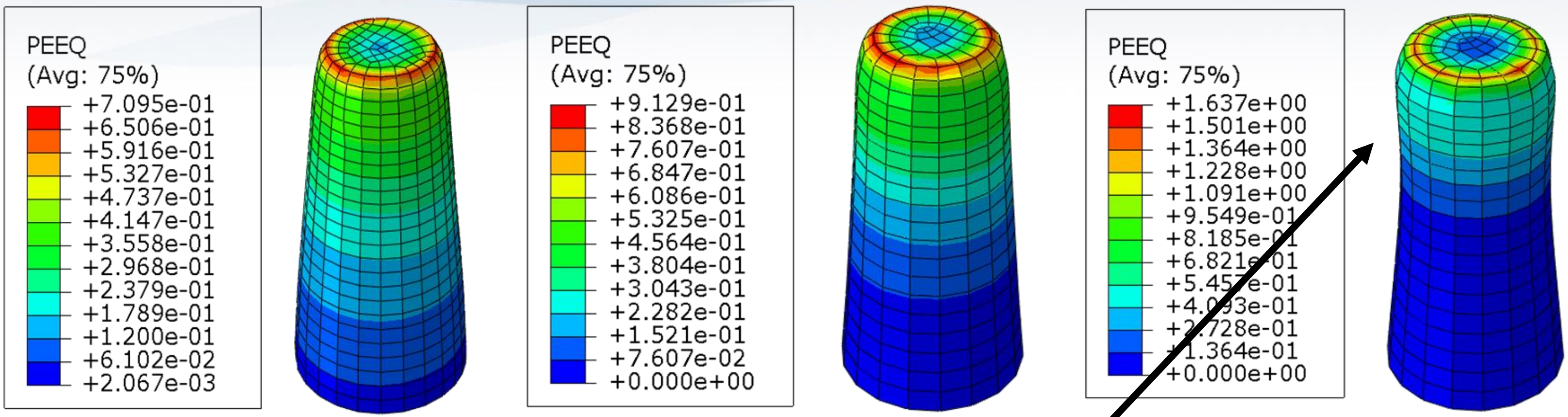
Intermediate strain hardening



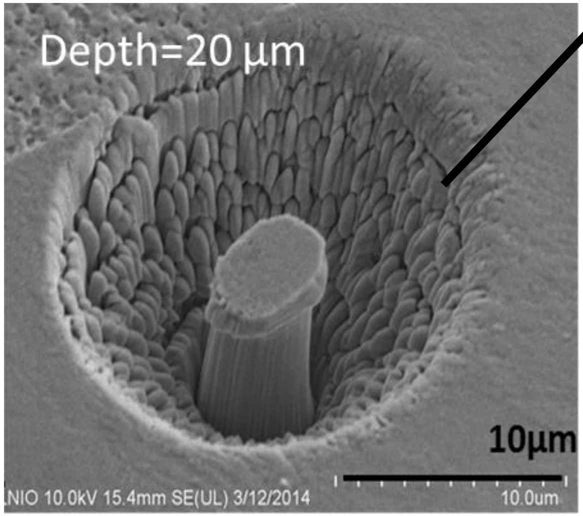
Low strain hardening

Numerical simulation

- <u>Stress and strain fields:</u>



High strain hardening **Intermediate strain hardening** **Low strain hardening**



Consistent

Conclusions et prospects

- The technique of micro-pillar compression has been utilized to study the mechanical properties of a material treated by SMAT.

- Observation by EBSD (orientation, grain size gradient) and by TEM (deformation mechanism).

- Development of a model to describe the behavior of grain boundary in order to study the mechanical behavior of the nanocrystalline layer.

Thank you !

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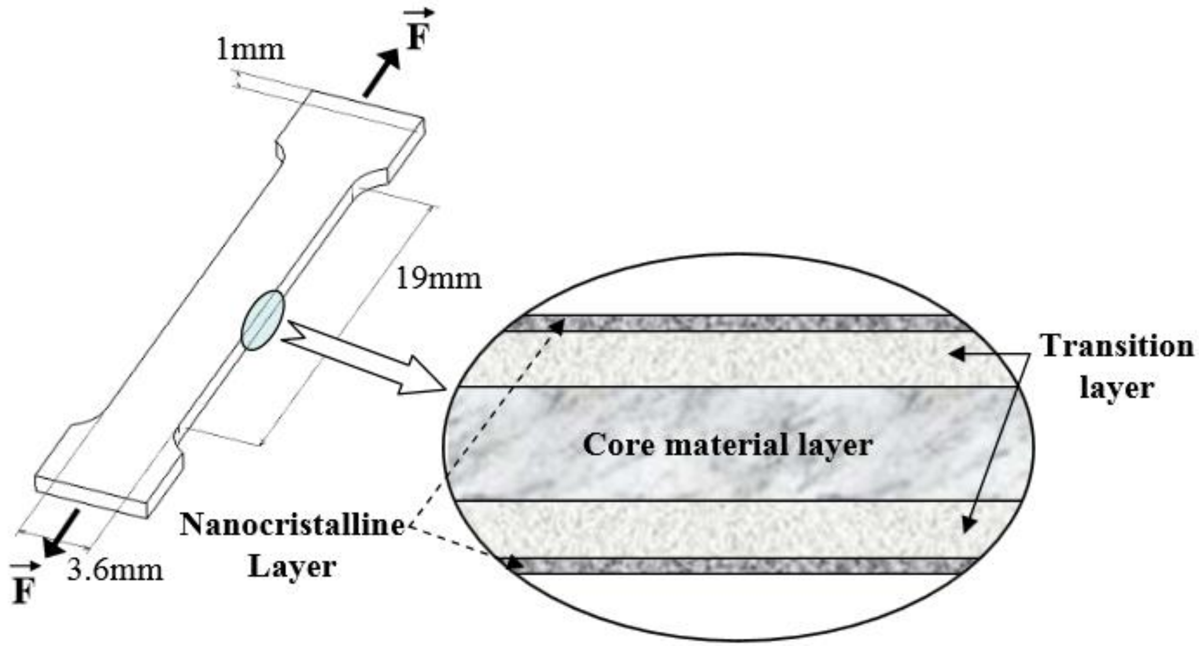
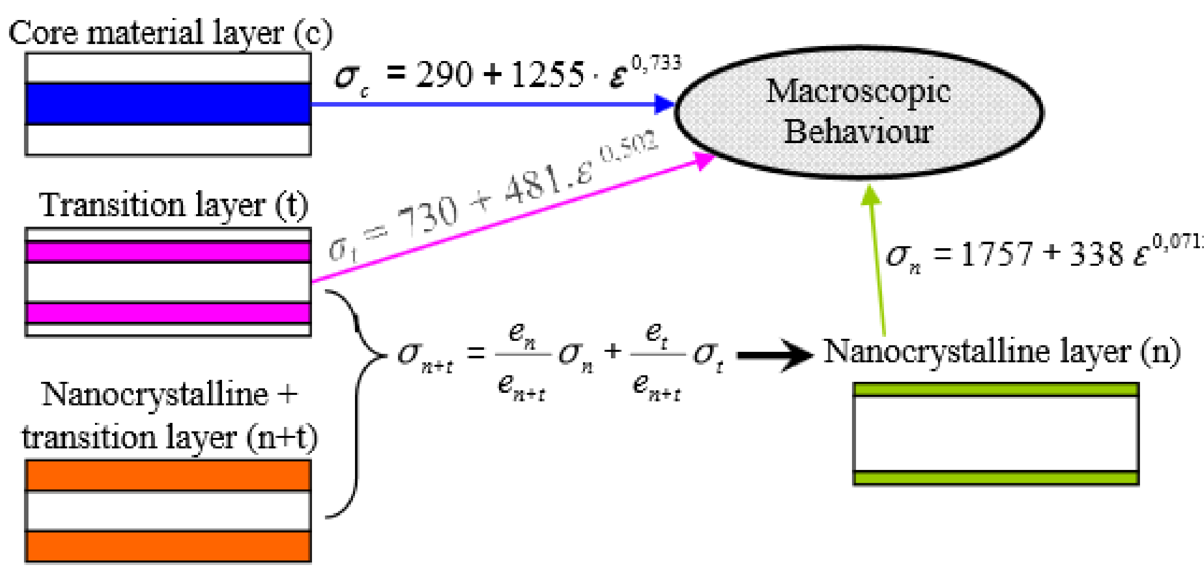
Differences: SMAT and Shot Peening

- The impact shots are bigger
- The impact shots are perfectly spherical.
- Speed of the impact shots: 5 – 20 m/s
- The impact angle is completely random.


1mm
F
19mm
Transition layer
Core material layer
Nanocristalline Layer
3.6mm
F


Core material layer (c)
$\sigma_c = 290 + 1255 \cdot \varepsilon^{0,733}$
Macroscopic Behaviour
Transition layer (t)
$\sigma_t = 730 + 481.\varepsilon^{0,502}$
$\sigma_n = 1757 + 338\ \varepsilon^{0,0712}$
$\sigma_{n+t} = \frac{e_n}{e_{n+t}}\sigma_n + \frac{e_t}{e_{n+t}}\sigma_t$
Nanocrystalline layer (n)
Nanocrystalline + transition layer (n+t)