Mines ParisTech
A short personal view

Samuel Forest

Centre des Matériaux, Mines ParisTech CNRS,
PSL Research University, France

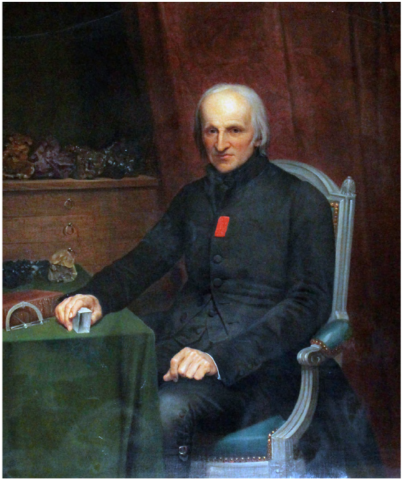
Mines ParisTech

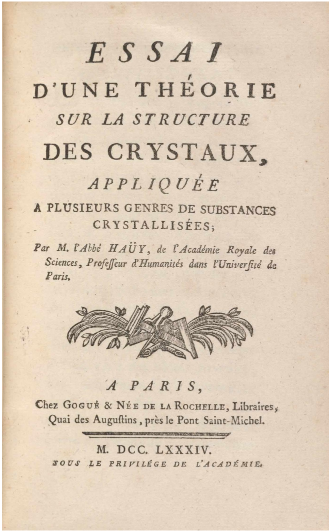
- The last royal engineering school created in 1783
- 180 “general” engineers and 100 PhD students graduate each year
- 250 permanent researchers and professors
- Research towards industry in: Materials sciences, Geosciences, Applied mathematics, Energy, Social sciences (Economics, sociology...)
- Several locations: Luxembourg garden, Evry, Fontainebleau, Sophia-Antipolis
- Member of ParisTech: A network of 10 graduate schools
- Member of PSL Research University, a community of 10 universities/schools
  Paris Sciences Lettres, 17000 students, 4500 researchers

Theory and practice

Déodat de Dolomieu gave its name to the Dolomites, a mountain range of northeastern Italy, to its building sedimentary rock, *dolomite*, and to a crater of the volcano *Piton de la Fournaise*.

René-Just Haüy: Founder of crystallography



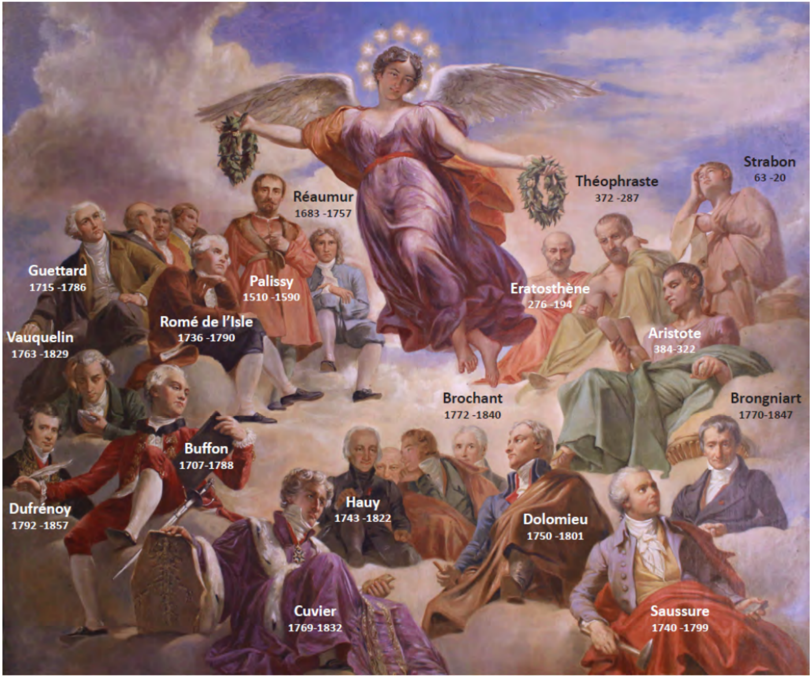


ESSAI
D'UNE THÉORIE
SUR LA STRUCTURE
DES CRYSTAUX,
APPLIQUÉE
A PLUSIEURS GENRES DE SUBSTANCES
CRYSTALLISÉES;

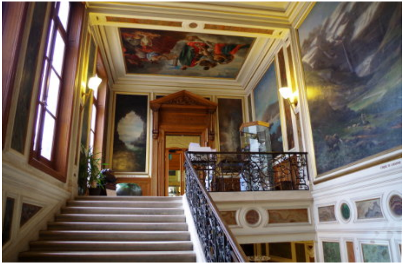
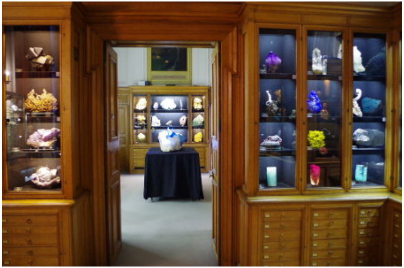
Par M. l'Abbé HAÜY, de l'Académie Royale des Sciences, Professeur d'Humanités dans l'Université de Paris.

A PARIS,
Chez GOGUÉ & NÉE DE LA ROCHELLE, Libraires, Quai des Augustins, près le Pont Saint-Michel.

M. DCC. LXXXIV.
SOUS LE PRIVILÉGE DE L'ACADÉMIE.


Strabon
63 -20
Théophraste
372 -287
Réaumur
1683 -1757
Guettard
1715 -1786
Palissy
1510 -1590
Eratosthène
276 -194
Romé de l'Isle
1736 -1790
Aristote
384-322
Vauquelin
1763 -1829
Brochant
1772 -1840
Brongniart
1770-1847
Buffon
1707-1788
Hauy
1743 -1822
Dolomieu
1750 -1801
Dufrénoy
1792 -1857
Cuvier
1769-1832
Saussure
1740 -1799

Mineralogy museum

One of the largest collection in the world: 100000 samples, 4000 exposed (British museum, Freiberg museum)
in connection with *Museum d'histoire naturelle*

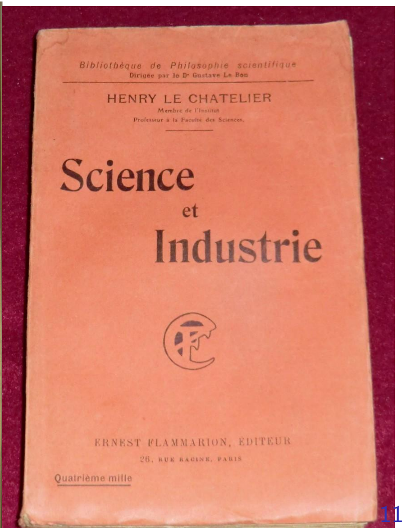
A president in the mineralogy museum

A president in the mineralogy museum

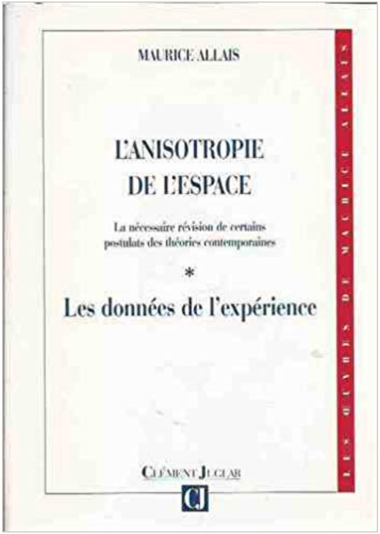
A president in the mineralogy museum

A president among the engineering students

Henry Le Chatelier



Maurice Allais: Nobel prize in economic sciences (1988)



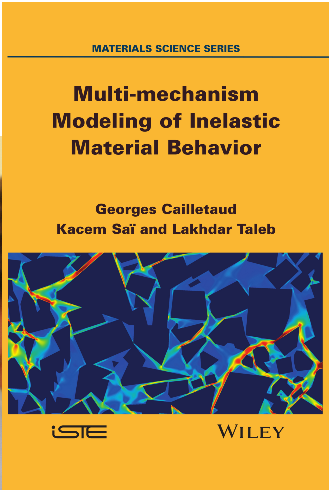
M. Allais wanted a Nobel prize in Physics!

Local approach to fracture

Fracture mechanics in nuclear engineering and aeronautics: Role of material microstructure

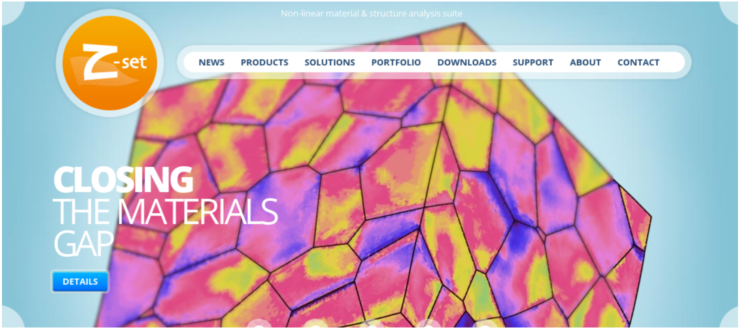
Dominique François, André Pineau and André Zaoui

Material modelling and computational mechanics



Georges Cailletaud and Jean-Louis Chaboche

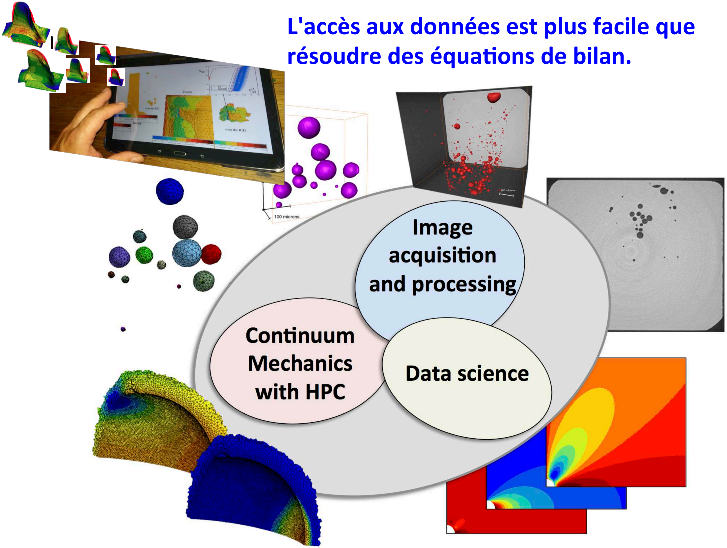
Z–set Non-linear material & structure analysis suite



www.zset-software.com

Mechanics and materials at the age of Big Data

L'accès aux données est plus facile que résoudre des équations de bilan.



Full order models (FOM) – Reduced order models (ROM) – Data science

Thanks to Carlo Sansour!

with Gérard Maugin (CISM course in Udine, Italy, 2007)

Modelling the mechanical behaviour of nickel base foams for DPF applications

A. Burteau, T. Dillard, J.D. Bartout, F. N'Guyen, S. Forest, Y. Bienvenu

Centre des Matériaux/UMR 7633
Mines Paris – ParisTech /CNRS
Samuel.Forest@ensmp.fr

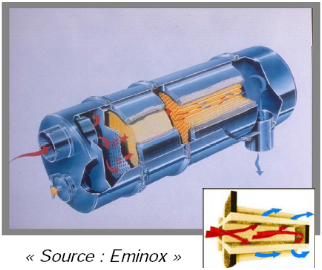
S. Saberi

INCO SP, Mississauga, Canada

Plan

Plan

1. Introduction
2. Microstructure evolution during material processing and deformation
   - Nickel based open cell foams
   - Microtomography analysis
3. Phenomenological modelling of plasticity and fracture
   - Micromorphic anisotropic compressible plasticity model
   - Simulation of crack propagation
4. Micromechanical approach
   - Strut behaviour
   - Representative Volume Element size
5. Conclusions



« Source : Eminox »

- Environment : protocol of Kyoto (1997)
- Petrol engine vs. Diesel engine
- Reduction of greenhouse gas

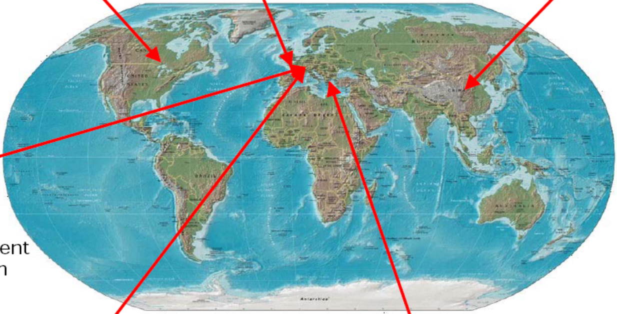
  => increase in the rejection of particles
- EURO V standard in 2008

- Necessity of the PF: technology « ceramics » vs. « metals »
- Advantage of metallic PF:
  - better catalytic efficiency
  - easier designed
  - easier recycled

- Mechanical properties
- Characterization of the foams

- Management
- Optimisation of the filters

- Production of PU and nickel foams



- Alloy development
- Industrialisation

- Catalytic coating

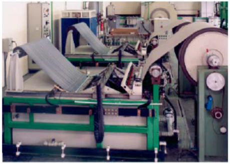
- Thermodynamics
- Test in working conditions

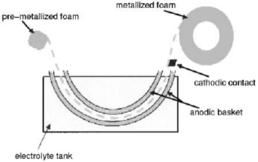
Plan

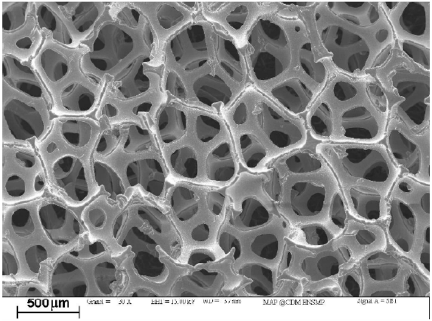
Plan

Processing of nickel foams

from PU template

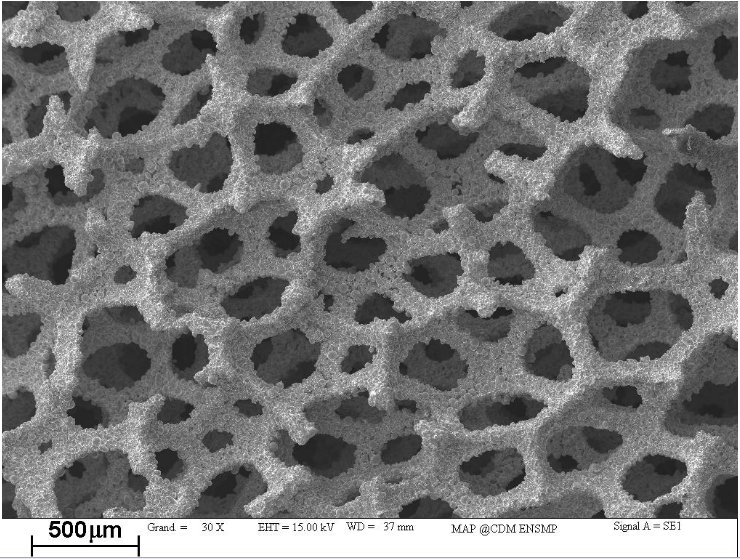




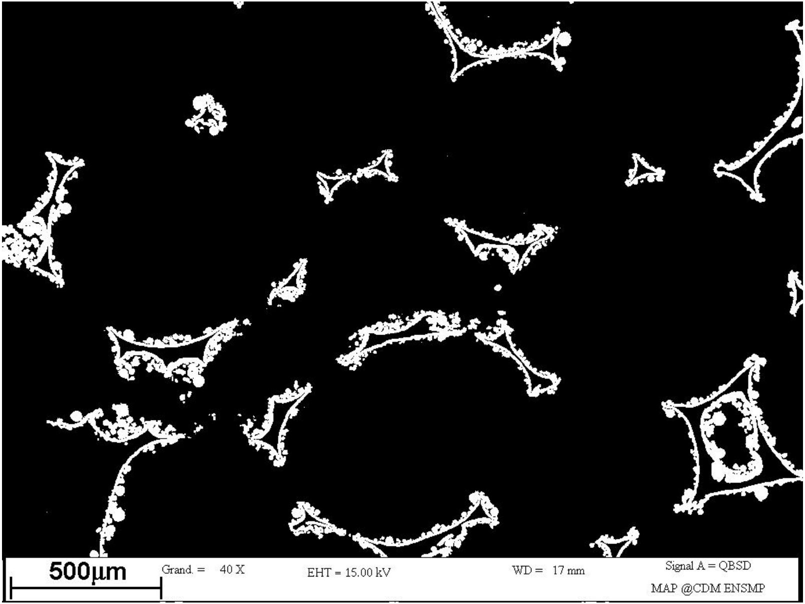


Microstructure of superalloy foam

composition close to IN625



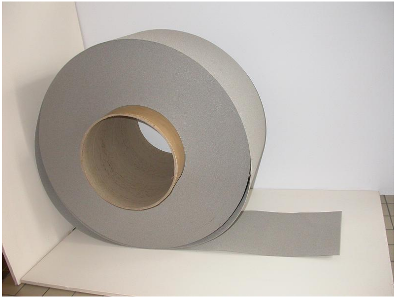
Microstructure of superalloy foam

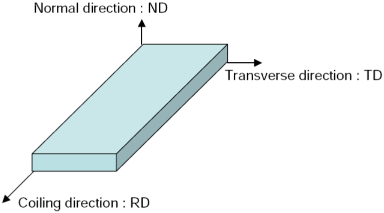


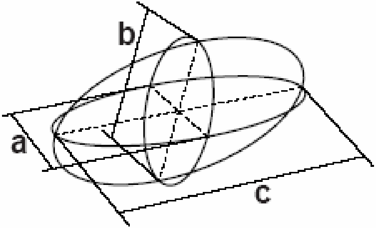
Plan

1. Introduction
2. Microstructure evolution during material processing and deformation
   - Nickel based open cell foams
   - Microtomography analysis
3. Phenomenological modelling of plasticity and fracture
   - Micromorphic anisotropic compressible plasticity model
   - Simulation of crack propagation
4. Micromechanical approach
   - Strut behaviour
   - Representative Volume Element size
5. Conclusions

Foam sheet axes and cell shape

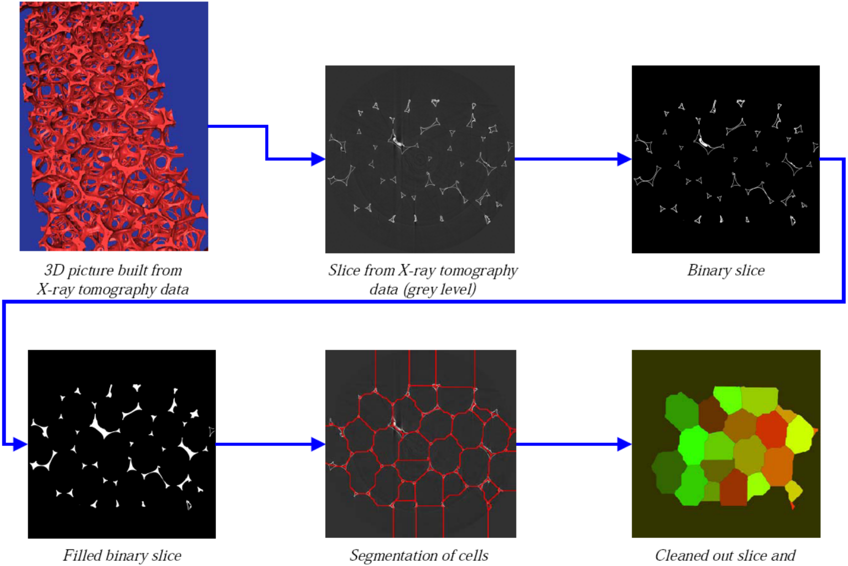




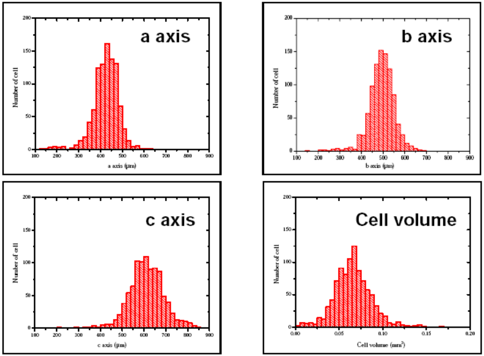


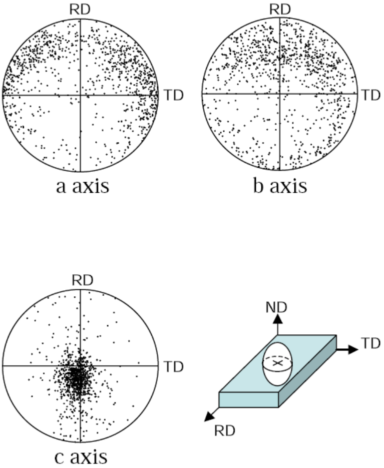
$$a \leq b \leq c$$

3D image analysis from X–ray microtomography experiments at ESRF



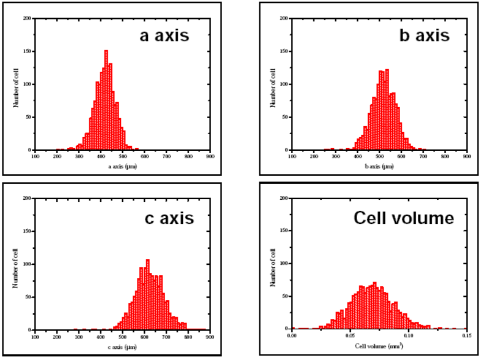
Cell shape in PU580 template foam



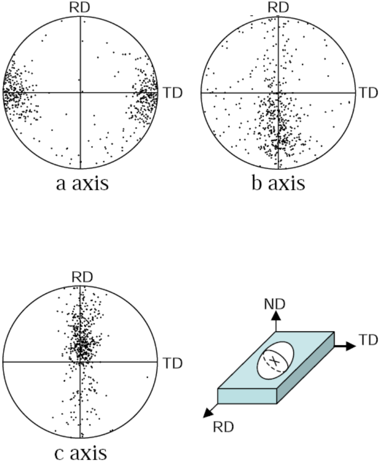


(964)	a axis	b axis	c axis	Cell volume
unit	μm	μm	μm	mm^3
mean	424	492	612	0.066
Std dev	57	60	81	0.021

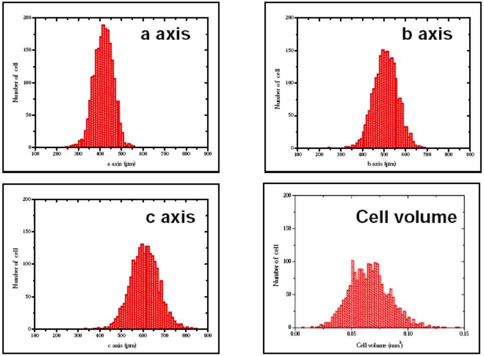
Cell shape in Ni580 foam

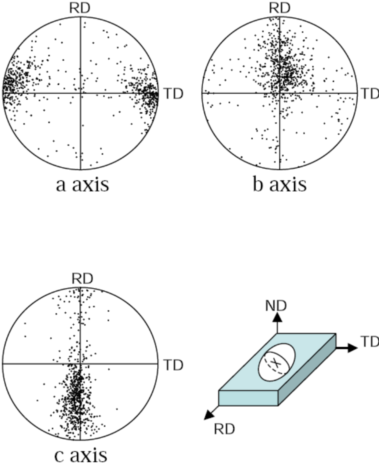


(1502)	a axis	b axis	c axis	Cell volume
unit	µm	µm	µm	mm^3
mean	418	517	622	0.0687
Std dev	48	56	70	0.019



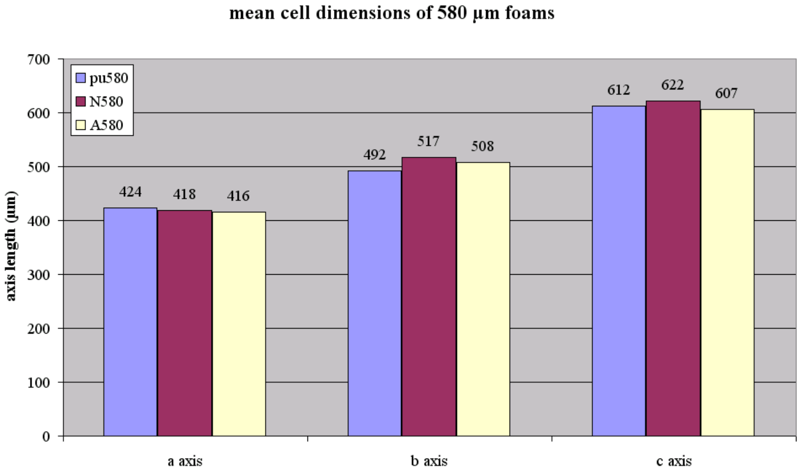
Cell shape in A580 foam



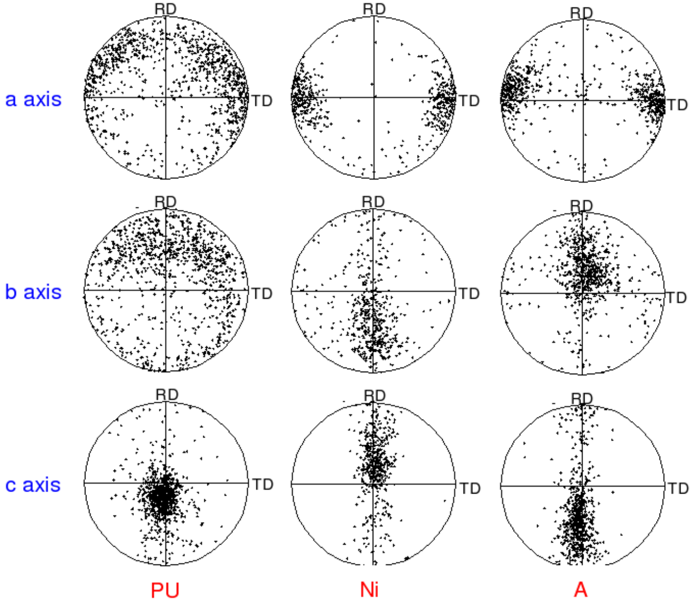


(2071)	a axis	b axis	c axis	Cell volume
unit	µm	µm	µm	mm^3
mean	416	508	607	0.066
Std dev	44	55	65	0.018

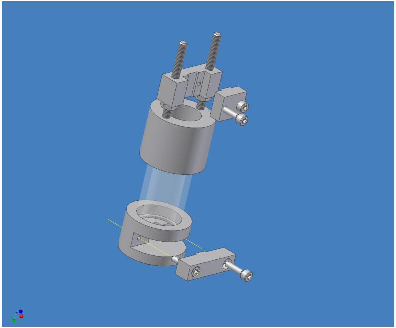
Evolution of cell shape during the process



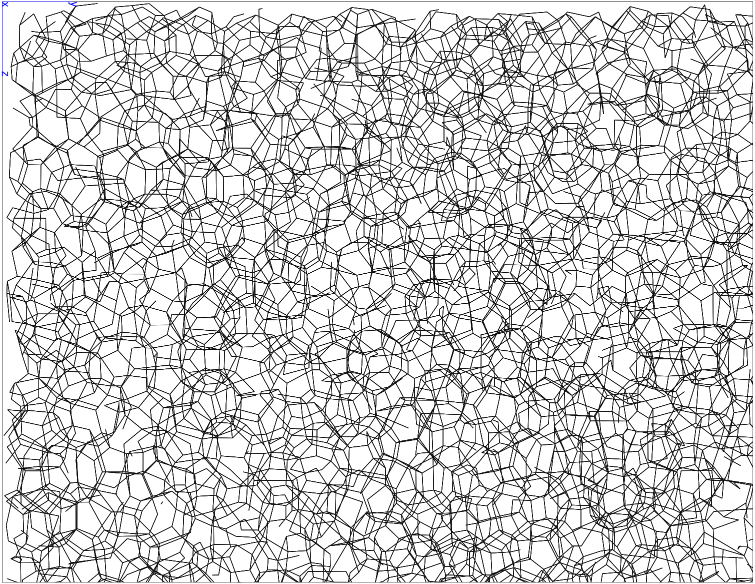
Evolution of cell orientation during the process



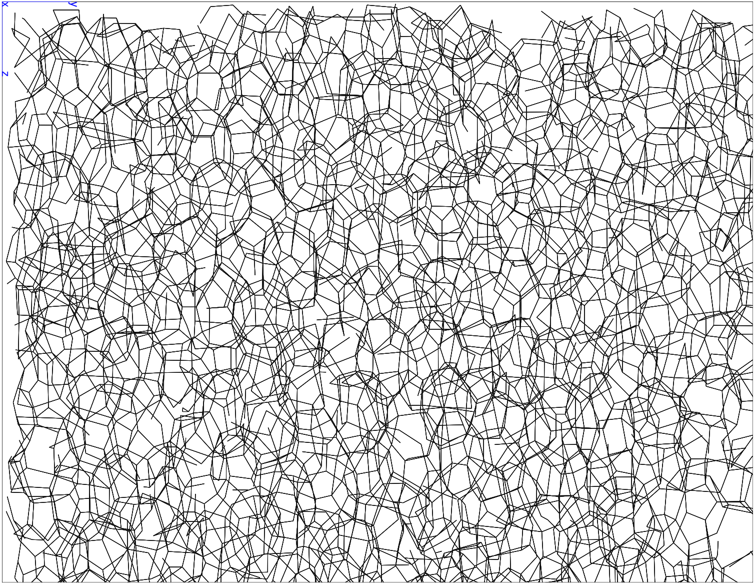
Deformation of PU foam



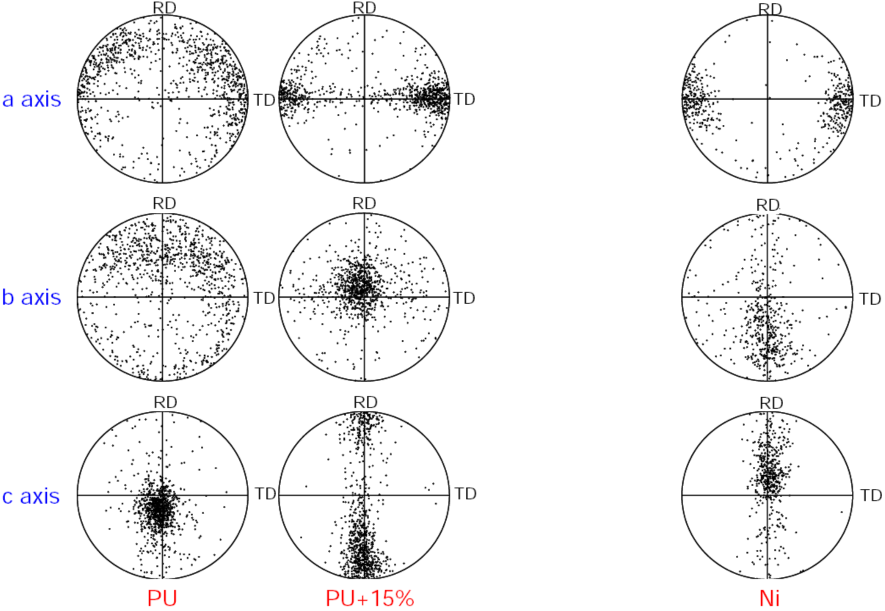
Evolution of cell orientation after deformation



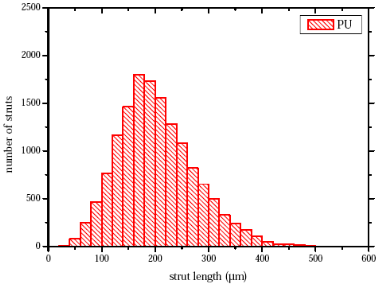
Evolution of cell orientation after deformation

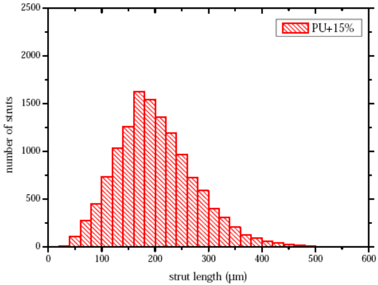


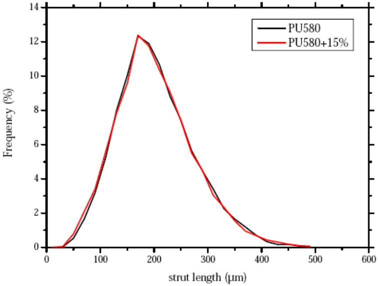
Evolution of cell orientation after deformation



Evolution of strut length after deformation







	PU	PU+15%
Strut length (µm)	203	202

Plan

Plan

Anisotropic Compressible Continuum Plasticity Model

Yield criterion

$$f(\underset{\sim}{\sigma}) = \sigma_{eq} - R, \quad \sigma_{eq} = \left(\frac{3}{2} C \underset{\sim}{\sigma}^{\mathrm{dev}} : \underset{\approx}{\mathbf{H}} : \underset{\sim}{\sigma}^{\mathrm{dev}} + F(\underset{\sim}{\mathbf{P}} : \underset{\sim}{\sigma})^2\right)^{\frac{1}{2}}$$

$$[H] = \begin{bmatrix} h_a & 0 & 0 & 0 & 0 & 0 \\ 0 & h_b & 0 & 0 & 0 & 0 \\ 0 & 0 & h_c & 0 & 0 & 0 \\ 0 & 0 & 0 & h_d & 0 & 0 \\ 0 & 0 & 0 & 0 & h_e & 0 \\ 0 & 0 & 0 & 0 & 0 & h_f \end{bmatrix}, \quad [P] = \begin{bmatrix} p & 0 & 0 \\ 0 & q & 0 \\ 0 & 0 & r \end{bmatrix}$$

Normality rule $\quad \dot{\underset{\sim}{\varepsilon}}^p = \dot{p} \frac{\partial f}{\partial \underset{\sim}{\sigma}} = \dot{p} \left(\frac{3}{2} C \underset{\approx}{\mathbf{H}} : \underset{\sim}{\sigma}^{\mathrm{dev}} + F(\underset{\sim}{\mathbf{P}} : \underset{\sim}{\sigma})\, \underset{\sim}{\mathbf{P}}\right)$

Consistency condition (cumulative plastic strain p)

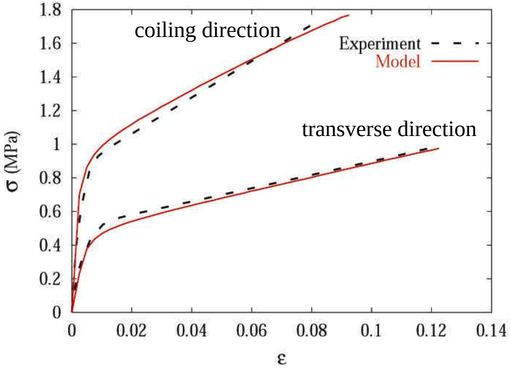
$$\dot{p} = \frac{\dfrac{\partial f}{\partial \underset{\sim}{\sigma}} : \underset{\approx}{\mathbf{E}} : \dot{\underset{\sim}{\varepsilon}}}{\dfrac{\partial f}{\partial \underset{\sim}{\sigma}} : \underset{\approx}{\mathbf{E}} : \dfrac{\partial f}{\partial \underset{\sim}{\sigma}} + \dfrac{\partial R}{\partial p}}$$

Nonlinear isotropic hardening

$$R = R_0 + Hp + Q(1 - \exp(-bp))$$

Parameter identification

C	F	R_0 (MPa)	Q (MPa)	b	H (MPa)	h_a	h_b	h_c	h_d	h_e	h_f
1	$6{,}8.10^{-4}$	0,30	0,37	3,3	8,17	0,41	1,8	1,75	1,45	1	1



p	q	r
1	37	23

Metal foam as a micromorphic continuum : The *microfoam* model

Degrees of freedom at material point

$$\text{displacement vector } \underline{\mathbf{u}}\,, \quad \text{microdeformation tensor } \underset{\sim}{\chi}$$

after [Mindlin, 1964] [Eringen, 1964]

Deformation measures

$$\text{strain tensor} \quad \underset{\sim}{\varepsilon} = (\underline{\mathbf{u}} \otimes \boldsymbol{\nabla} + \boldsymbol{\nabla} \otimes \underline{\mathbf{u}})/2$$

$$\text{relative deformation tensor} \quad \underset{\sim}{\mathbf{e}} = \underline{\mathbf{u}} \otimes \boldsymbol{\nabla} - \underset{\sim}{\chi}$$

$$\text{microdeformation gradient} \quad \underset{\approx}{\mathbf{K}} = \underset{\sim}{\chi} \otimes \boldsymbol{\nabla}$$

Power density of internal forces / generalized stress tensors

$$p^{(i)} = \underset{\sim}{\sigma} : \dot{\underset{\sim}{\varepsilon}} + \underset{\sim}{\mathbf{s}} : \dot{\underset{\sim}{\mathbf{e}}} + \underset{\approx}{\mathbf{M}} \vdots \dot{\underset{\approx}{\mathbf{K}}}$$

Balance of momentum $\qquad (\underset{\sim}{\sigma} + \underset{\sim}{\mathbf{s}}).\boldsymbol{\nabla} = 0$

Balance of micromorphic momentum $\qquad \underset{\approx}{\mathbf{M}}.\boldsymbol{\nabla} + \underset{\sim}{\mathbf{s}} = 0$

Boundary conditions (traction and double traction vectors)

$$\underline{\mathbf{t}} = (\underset{\sim}{\sigma} + \underset{\sim}{\mathbf{s}}).\underline{\mathbf{n}}\,, \quad \underset{\sim}{\mathbf{T}} = \underset{\approx}{\mathbf{M}}.\underline{\mathbf{n}}$$

Variational formulation for finite element implementation

$$\int_V p^{(i)}\, dV = \int_{\partial V} \left(\underline{\mathbf{t}}\,.\dot{\underline{\mathbf{n}}} + \underset{\sim}{\mathbf{T}} : \dot{\underset{\sim}{\chi}} \right) dS$$

The *microfoam* model : Constitutive equations

Strain partition

$$\underset{\sim}{\varepsilon} = \underset{\sim}{\varepsilon}^e + \underset{\sim}{\varepsilon}^p, \quad \underset{\sim}{\mathbf{e}} = \underset{\sim}{\mathbf{e}}^e + \underset{\sim}{\mathbf{e}}^p, \quad \underset{\approx}{\mathbf{K}} = \underset{\approx}{\mathbf{K}}^e + \underset{\approx}{\mathbf{K}}^p$$

Linear elasticity

$$\underset{\sim}{\boldsymbol{\sigma}} = \underset{\approx}{\mathbf{c}} : \underset{\sim}{\varepsilon}^e, \quad \underset{\sim}{\mathbf{s}} = \underset{\approx}{\mathbf{a}} : \underset{\sim}{\mathbf{e}}^e, \quad \underset{\approx}{\mathbf{M}} = \underset{\approx\approx}{\mathbf{A}} \vdots \underset{\approx}{\mathbf{K}}^e$$

simplified moduli as proposed by [Shu et al., 1999] $\underset{\approx}{\mathbf{M}} = l_c^2 \, \underset{\approx}{\mathbf{c}} : \underset{\approx}{\mathbf{K}}^e$
characteristic length l_c
when $||\underset{\approx}{\mathbf{a}}||$ is very large, and if $\underset{\sim}{\mathbf{e}}^p = 0$, then $\underline{\mathbf{u}} \otimes \boldsymbol{\nabla} \simeq \underset{\sim}{\boldsymbol{\chi}}$ (second gradient theory)

The *microfoam* model : Constitutive equations

Yield criterion

$$f(\underset{\sim}{\boldsymbol{\sigma}}) = \sigma_{eq} - R$$

$$\sigma_{eq} = \left(\frac{3}{2} C \underset{\sim}{\boldsymbol{\sigma}}^{\mathrm{dev}} : \underset{\approx}{\mathbf{H}} : \underset{\sim}{\boldsymbol{\sigma}}^{\mathrm{dev}} + F(\underset{\sim}{\mathbf{P}} : \underset{\sim}{\boldsymbol{\sigma}})^2 + a_1 \underset{\sim}{\mathbf{s}}^{\mathrm{dev}} : \underset{\sim}{\mathbf{s}}^{\mathrm{dev}} + a_2 \underset{\sim}{\mathbf{s}}^{\mathrm{dev}} : \underset{\sim}{\mathbf{s}}^{\mathrm{devT}} + \right.$$

$$\left. + b_1 \underset{\approx}{\mathbf{M}} \vdots \underset{\approx}{\mathbf{M}} \right)^{\frac{1}{2}}$$

Normality rule

$$\dot{\underset{\sim}{\boldsymbol{\varepsilon}}}^p = \dot{p}\, \frac{\partial f}{\partial \underset{\sim}{\boldsymbol{\sigma}}}, \quad \dot{\underset{\sim}{\mathbf{e}}}^p = \dot{p}\, \frac{\partial f}{\partial \underset{\sim}{\mathbf{s}}}, \quad \dot{\underset{\approx}{\mathbf{K}}}^p = \dot{p}\, \frac{\partial f}{\partial \underset{\approx}{\mathbf{M}}}$$

Microfoam: $a_1 = a_2 = a_3 = b_1 = 0, ||\underset{\sim}{\mathbf{a}}||\text{very large}$
constrained microdeformation (second gradient), linear relationship between gradient of microdeformation and hyperstress tensor

Microstrain **continuum**

degrees of freedom $(\underline{\mathbf{u}}\,, \underset{\sim}{\boldsymbol{\chi}}^s)$
strain measures :
$(\underset{\sim}{\varepsilon}, \underset{\sim}{\varepsilon} - \underset{\sim}{\boldsymbol{\chi}}^s, \underset{\sim}{\boldsymbol{\chi}}^s \otimes \boldsymbol{\nabla})$

$$S_{ijk,k} + s_{ij} = 0$$

$$A\chi^s_{ij,kk} + b(\varepsilon_{ij} - \chi^s_{ij}) = 0$$

$$\underset{\sim}{\boldsymbol{\sigma}} = \underset{\approx}{\mathbf{C}} : (\underset{\sim}{\varepsilon} - \underset{\sim}{\varepsilon}^p)$$

$$\underset{\sim}{\mathbf{s}} = b(\underset{\sim}{\varepsilon} - \underset{\sim}{\boldsymbol{\chi}}^s)$$

$$\underset{\approx}{\underline{\mathbf{S}}} = A\underset{\sim}{\boldsymbol{\chi}}^s \otimes \boldsymbol{\nabla}$$

$$\varepsilon_{ij} = \chi^s_{ij} - l^2 \Delta \chi^s_{ij}$$

Link with "implicit gradient–enhanced elastoplasticity models" [Engelen *et al.*, 2003]

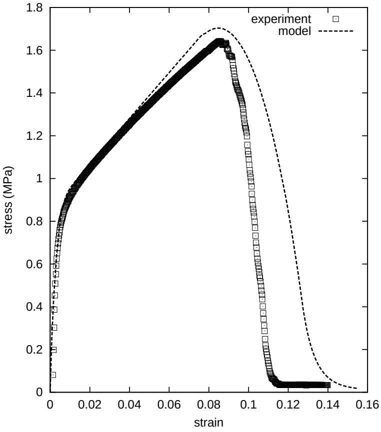
$$\mathrm{div}\,(\underset{\sim}{\boldsymbol{\sigma}} + \underset{\sim}{\mathbf{s}}) = 0$$

$$\mathrm{div}\,\underset{\approx}{\underline{\mathbf{S}}} + \underset{\sim}{\mathbf{s}} = 0$$

Boundary conditions :
(u_i, χ^s_{ij}) or
$(\sigma_{ij} + s_{ij})n_j, S_{ijk}n_k$

Plan

Fracture of nickel foams



tensile test in direction RD

simple fracture criterion

$$p = p_{crit} = 0.08$$

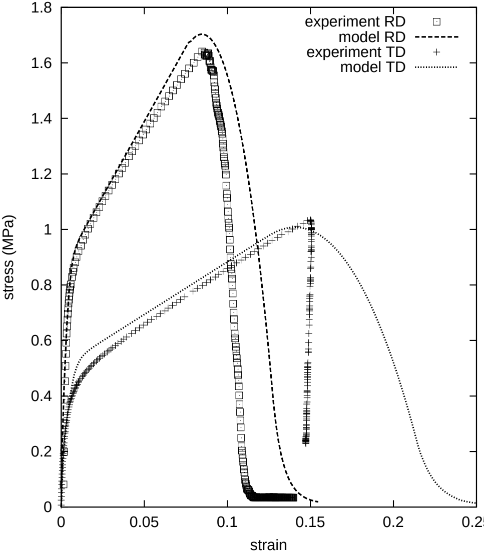
limited scatter in p_{crit}

softening law for $p > p_{crit}$

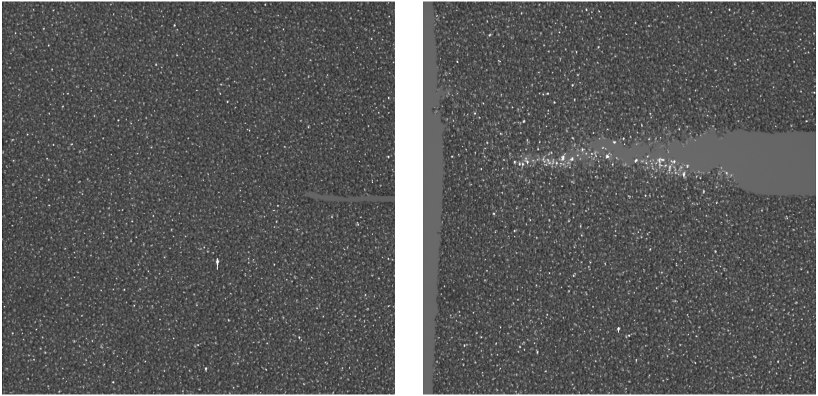
$$R = R(p > p_{crit})$$

Fracture anisotropy of nickel foams

prediction of fracture stress for tension along TD

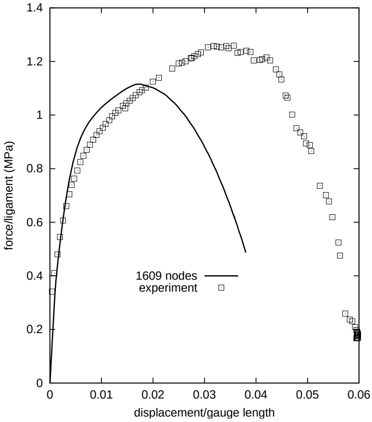


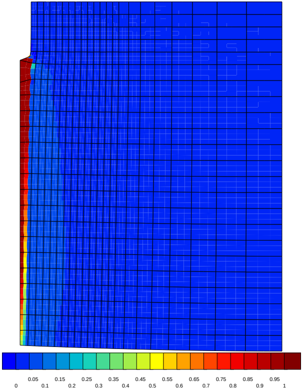
Tension of central crack nickel foam plate



crack length : 10 mm

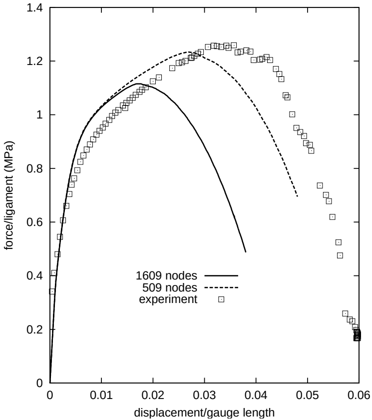
Simulation with a classical compressible plasticity model

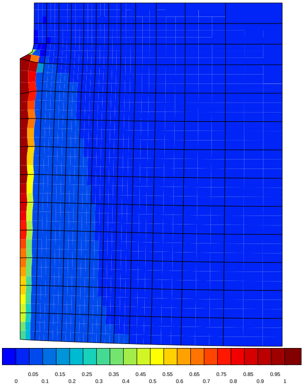




strain component ε_{11}

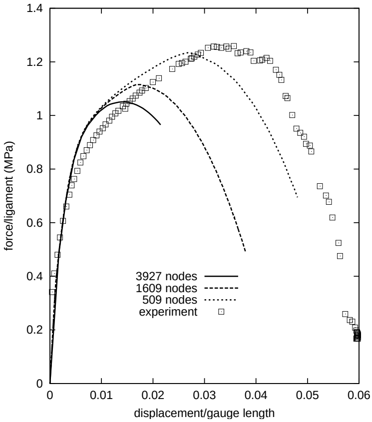
Simulation with a classical compressible plasticity model

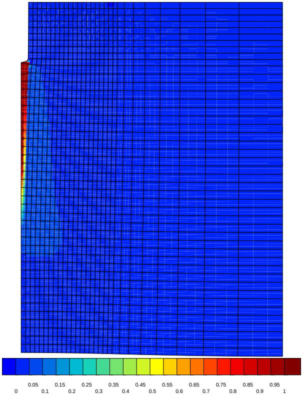




strain component ε_{11}

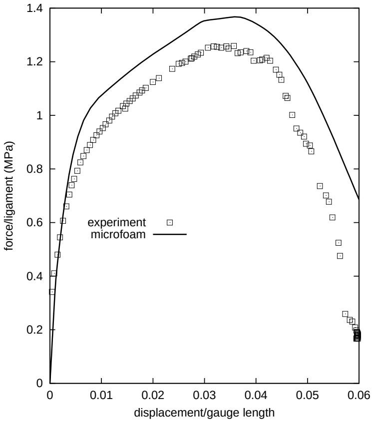
Simulation with a classical compressible plasticity model

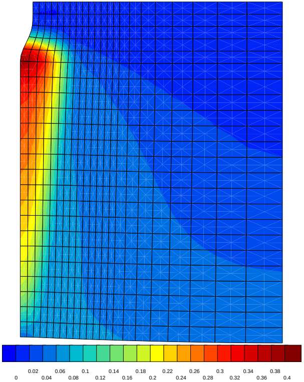




strain component ε_{11}

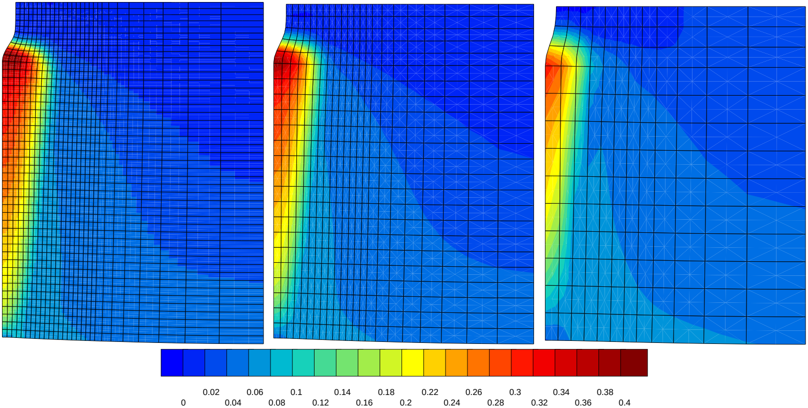
Simulation with the micromorphic foam model



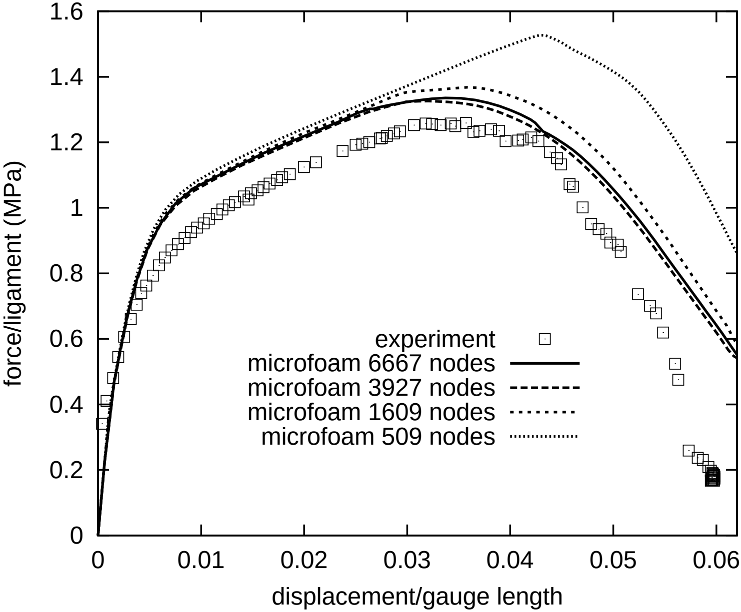


strain component ε_{11}

Damage zone size

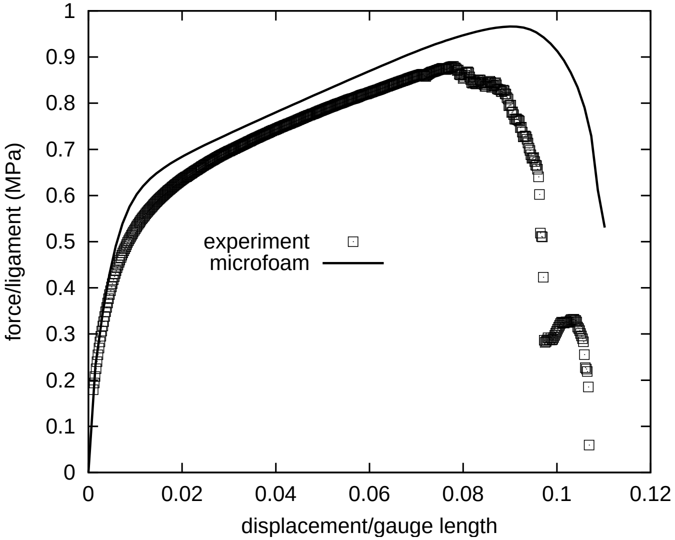


Convergence of the load–displacement curve



Fracture anisotropy of nickel foams

prediction of fracture stress for tension along TD

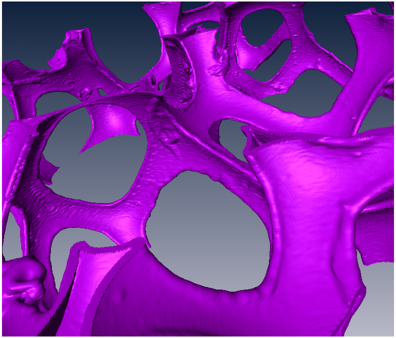


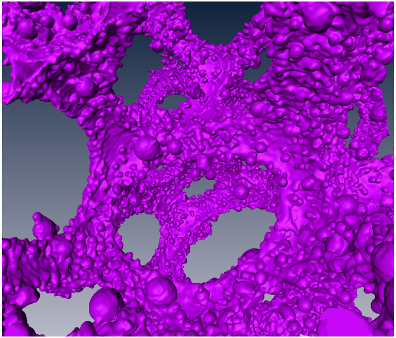
Plan

Plan

Ductility of nickel and alloyed foams

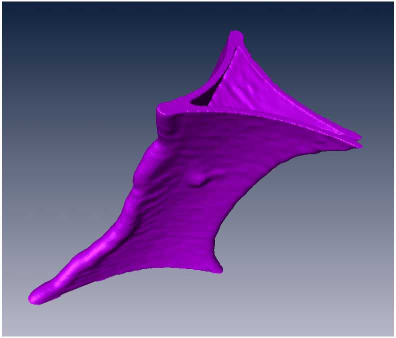
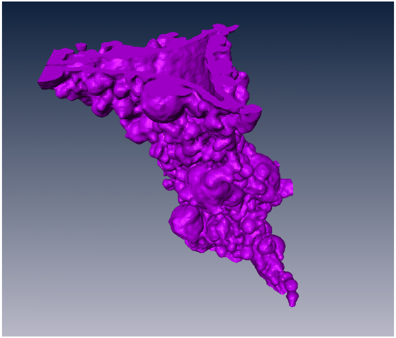
virtual machining a strut tensile/bending specimen out of the foam





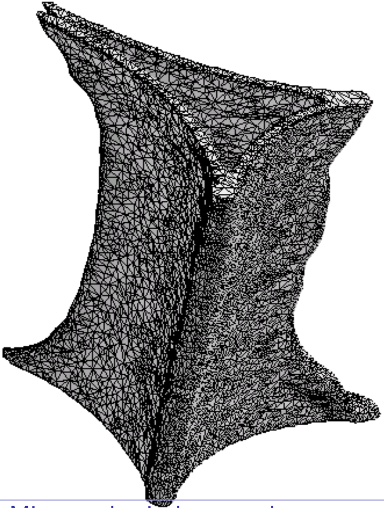
Ductility of nickel and alloyed foams

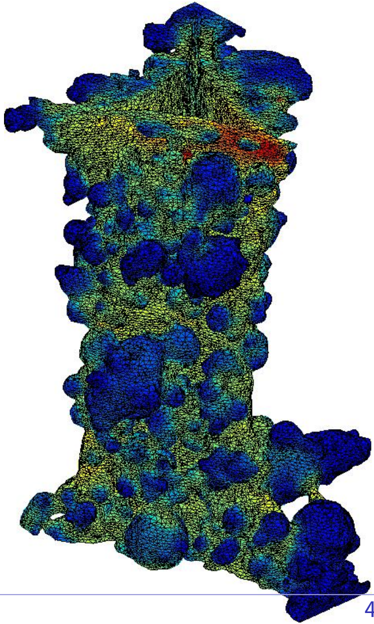
virtual machining of a strut specimen out of the foam

Ductility of nickel and alloyed foams

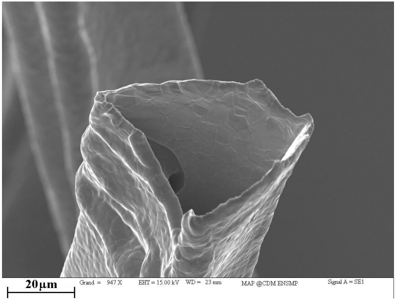
virtual tensile testing of a single strut

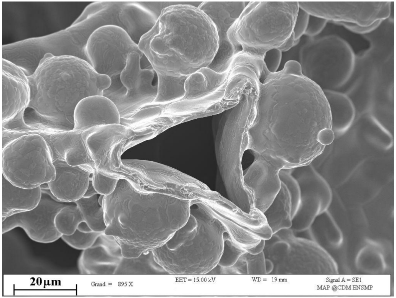




Ductility of nickel and alloyed foams

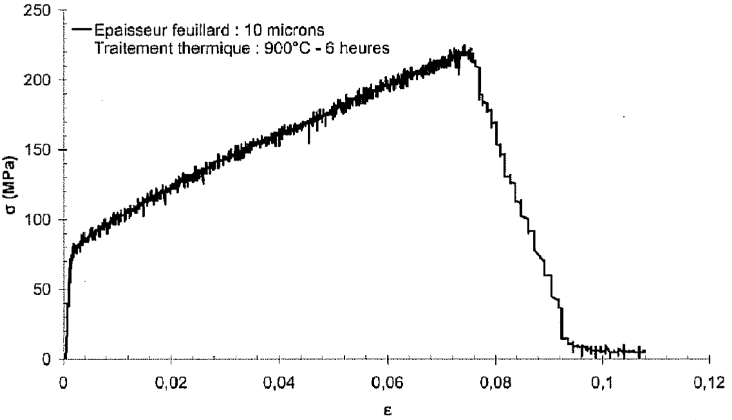
actual fracture surface of a strut





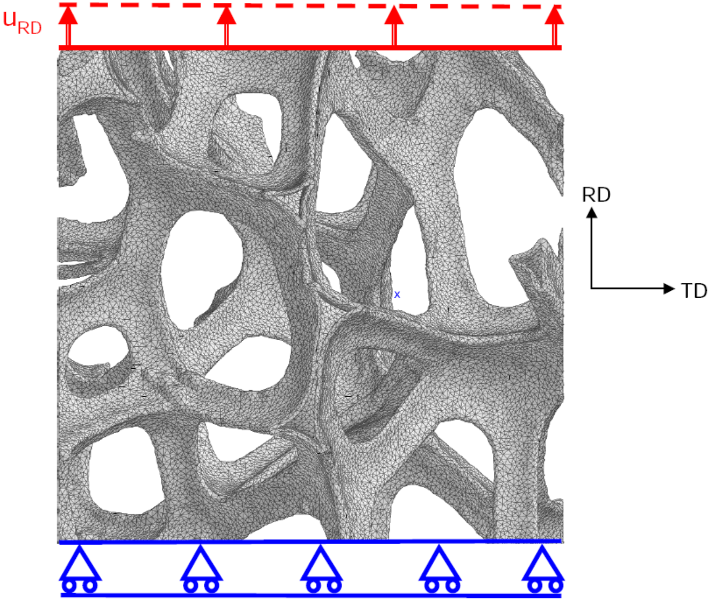
Plan

Behaviour of Nickel foils

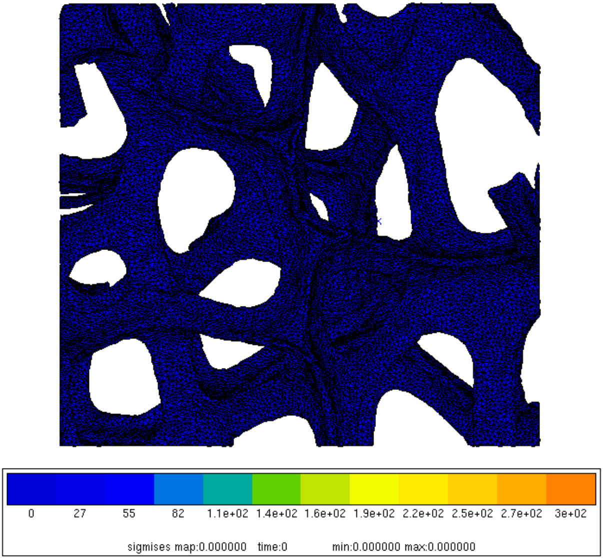


elastoplastic model with linear isotropic hardening

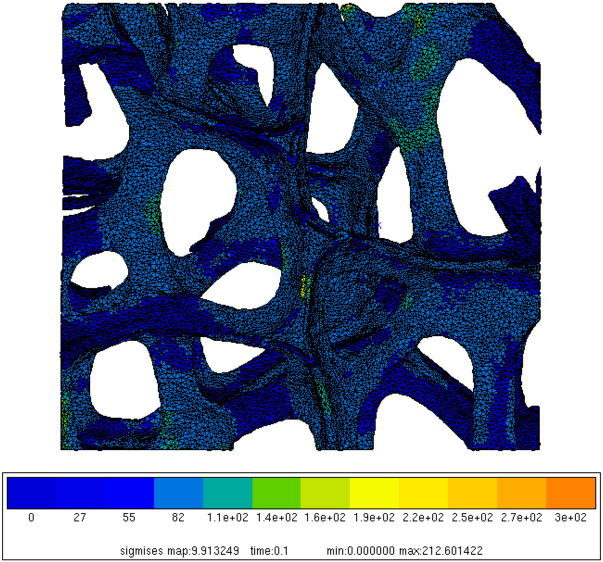
Computing one real single cell



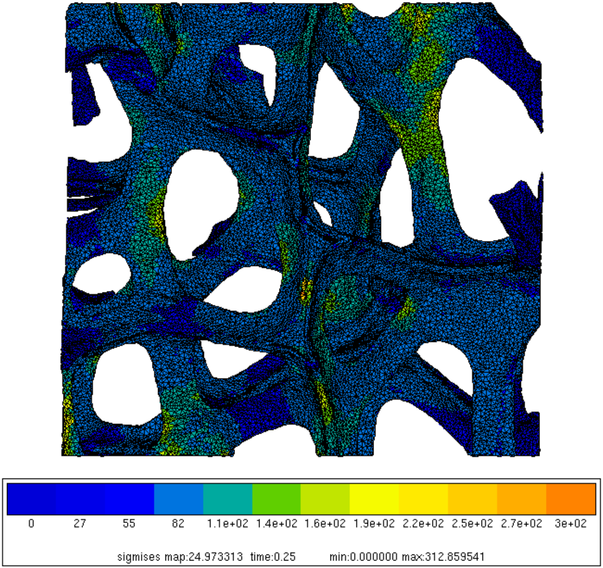
Computing one real single cell



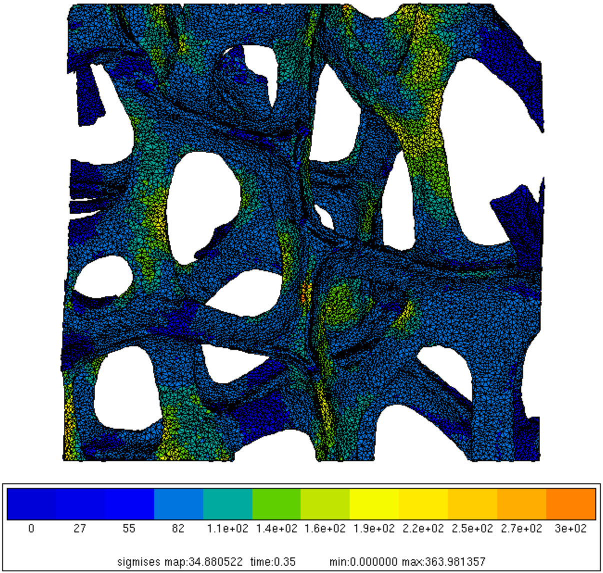
Computing one real single cell



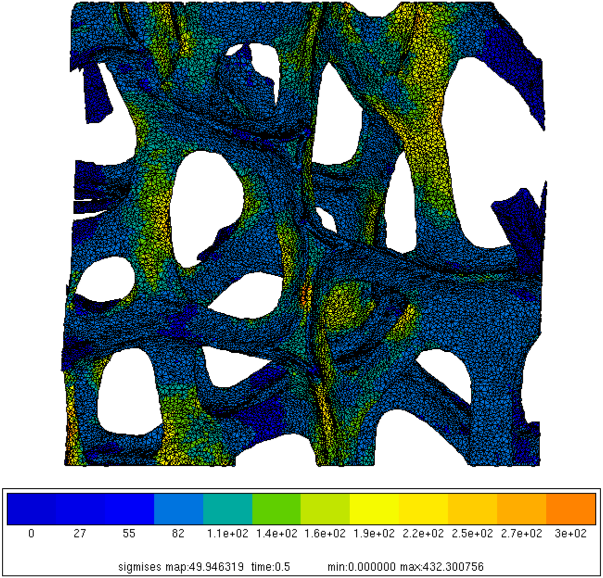
Computing one real single cell



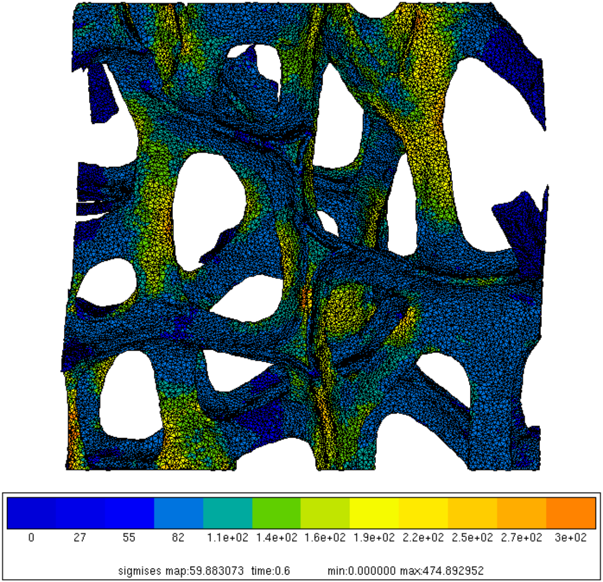
Computing one real single cell



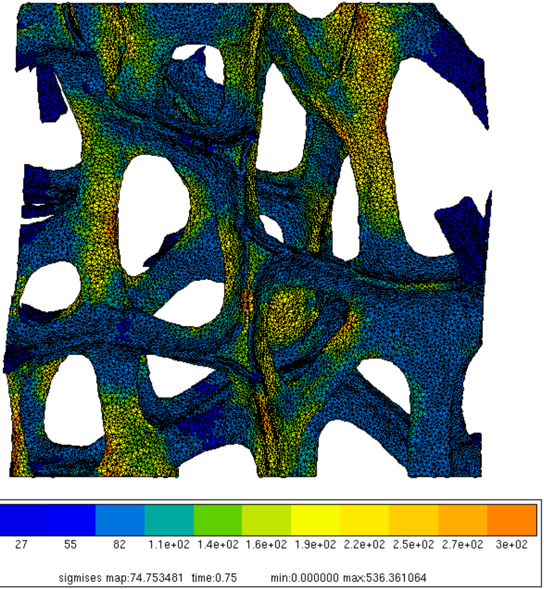
Computing one real single cell



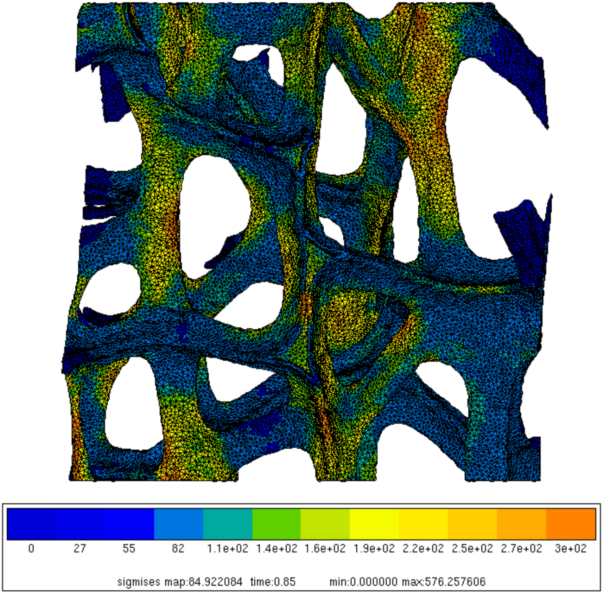
Computing one real single cell



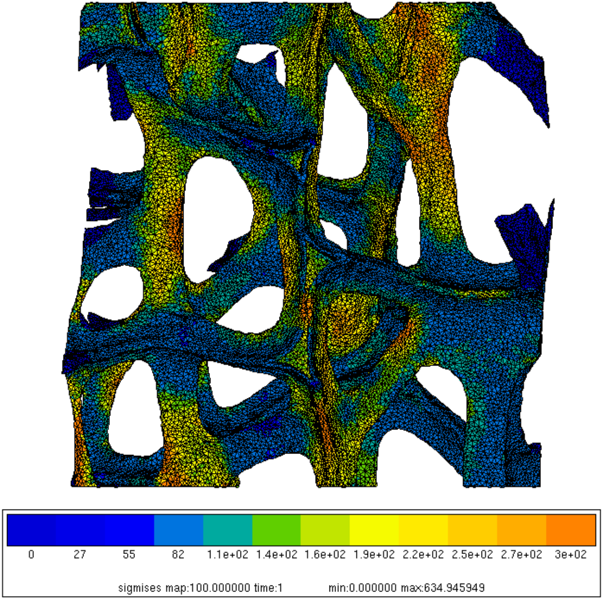
Computing one real single cell



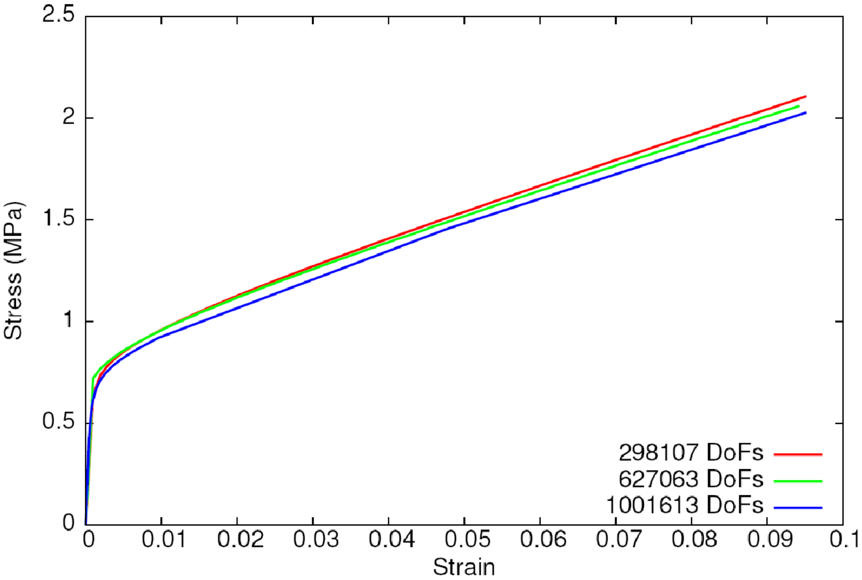
Computing one real single cell



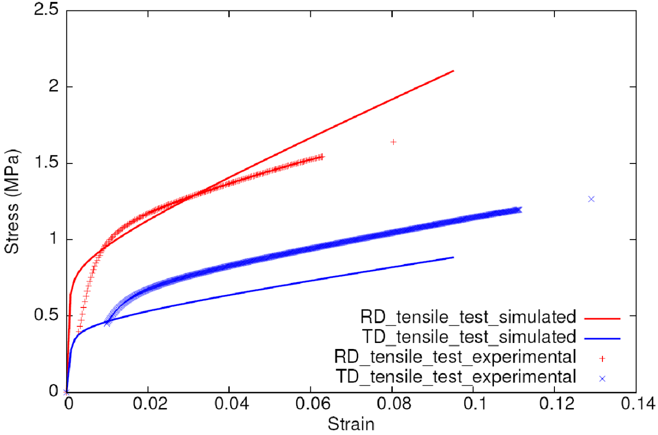
Computing one real single cell



Mesh sensitivity

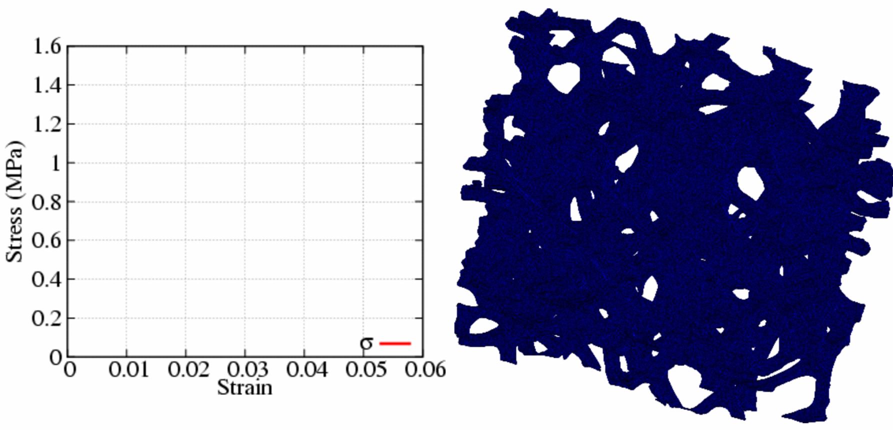


Prediction of elastoplastic properties



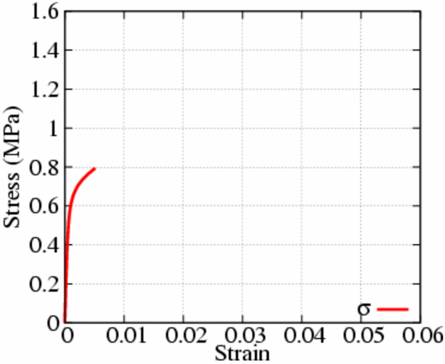
Young's modulus (GPa)	RD	TD	ND	E_{RD}/E_{TD}
simulation	1091	319	432	3.42
experiment	177	88		2

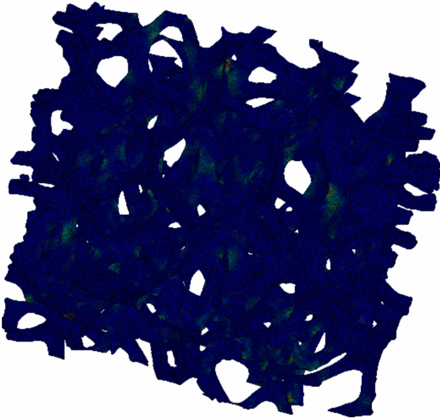
Eight cell volume element



3 600 000 DOF – 36 GB – 300 hours

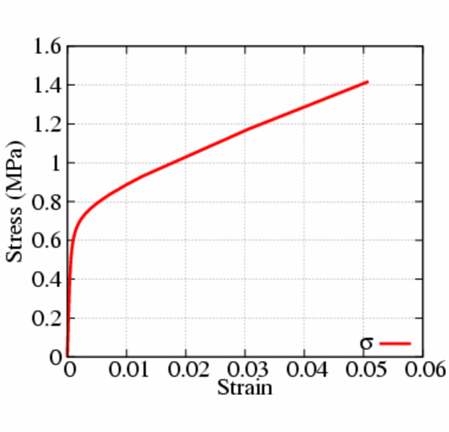
Eight cell volume element

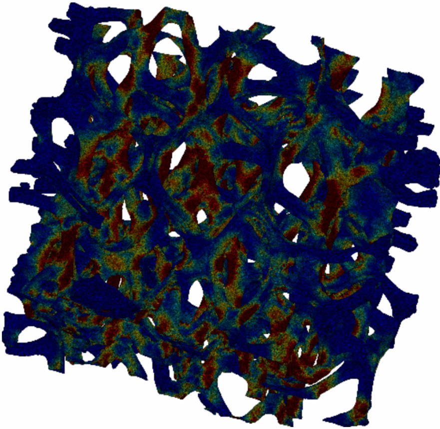




3 600 000 DOF – 36 GB – 300 hours – red: $p > 0.03$

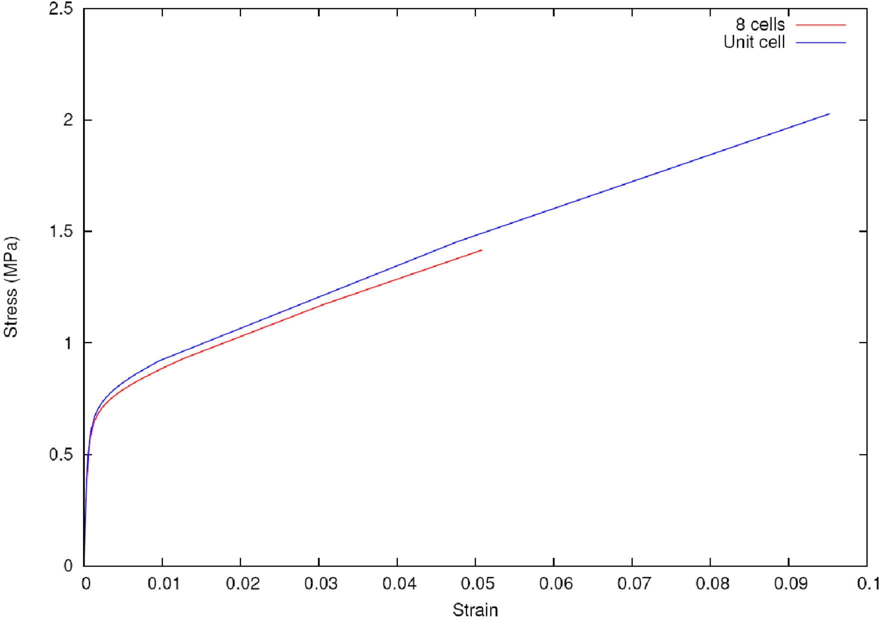
Eight cell volume element





3 600 000 DOF – 36 GB – 300 hours – red: $p > 0.03$

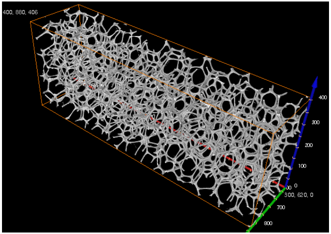
Eight cell vs. one cell volume element



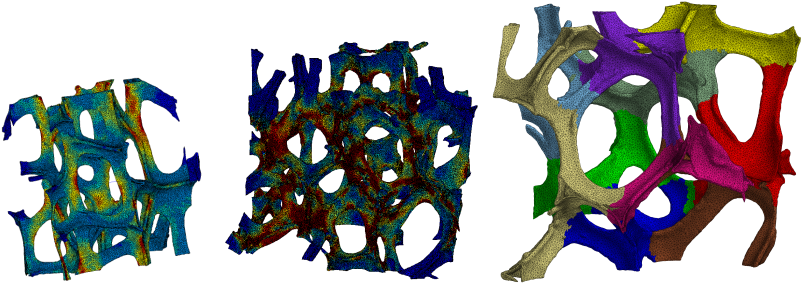
Plan

Perspectives

Deformation of cells by 3D microtomography (3D correlation techniques)



Systematic determination of RVE size for elastoviscoplastic properties of nickel base foams: cyclic loading, creep...



effect of BCs, statistical approach, parallel computing...