Virtual machining
Examples of numerical modelling
Macroscopic and Mesoscopic scales

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Team taking part in research on machining:

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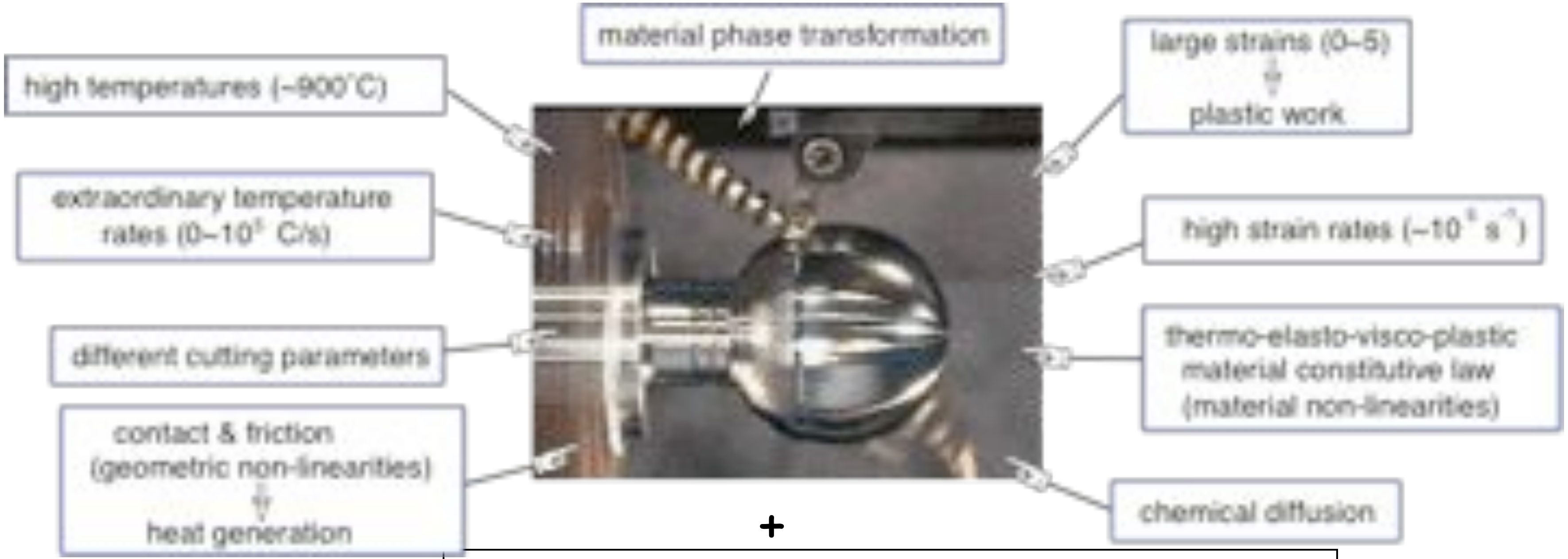
L. Illoul, C. Gengembre

Main Industrial partners:

SAFRAN/Snecma : aeronautics **(macroscopic scale)**
PCI/PSC : automobiles and engine manufacturers **(macroscopic scale)**
Cetim: Technical center for the mechanical industry **(macroscopic scale)**

Modelling machining

Numerical simulation of metal cutting processes is particularly complex due to the diversity of the physical phenomena involved, a real challenge to existing algorithms and computational tools



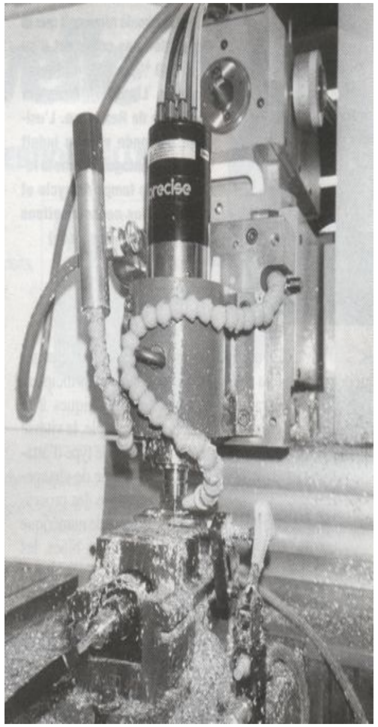
\+

Dynamical behaviour
- machine, spindle, tool vibrations,
- axis dynamical behaviour,
- workpiece (thin walled parts) + clamping flexibility

Its difficult to reproduce all the phenomenon in a single simulation → ***Multi-scale approach***

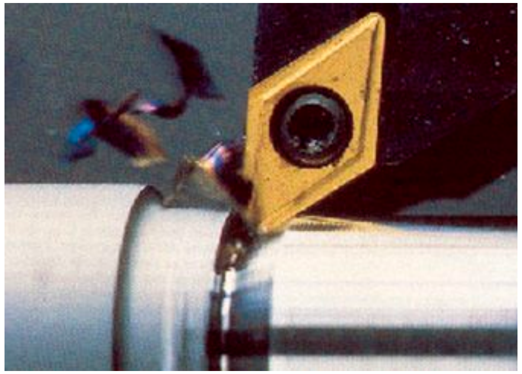
The different scales

Macroscopic



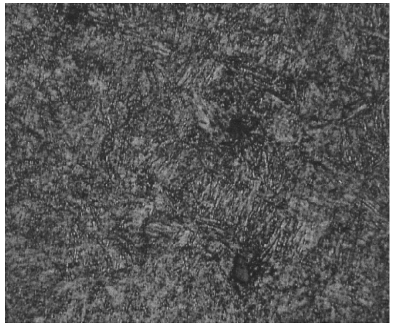
The whole Workpiece-Tool-Machine system

Mesoscopic



The neighbourhood of the tool tip

Microscopic



Grains of the mater

(1) M. Touratier, Technical report, LM2S – ENSAM Paris, 1998.

Macroscopic scale

System

Workpiece/Tool/Machine

Objectives

Machining system dynamics
Geometry of the machined surface
(form, waviness, roughness defects)
Cutting forces, power (history of ...)

Mechanical context

Nonlinear dynamics
Small strains
Known large displacement

Mesoscopic scale

System

Neighbourhood of the Tool tip

Objectives

Matter separation/Chip formation
Thermo-mechanical solicitations applied on :
- the tool (tool wear)
- the workpiece (surface integrity)

Mechanical context

Nonlinear thermo-mechanics with large displacement and large strains
multi-physics

Research at PiMM Laboratory

Milling / Turning → Flexible Part

Blanking / Cutting → C-Nem

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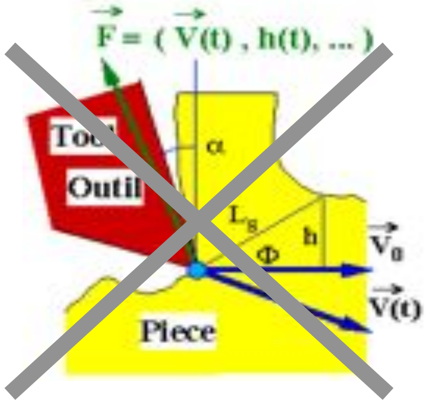
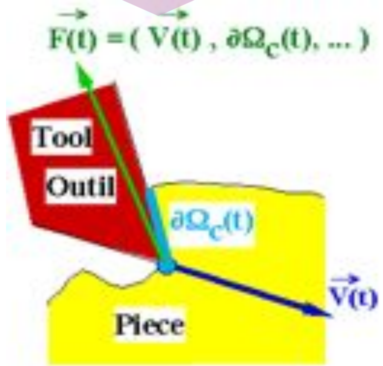
Research at PiMM Laboratory

Macroscopic scale : Tool/Part interaction model

→ Chip formation is not modelled



The tool erase the mater

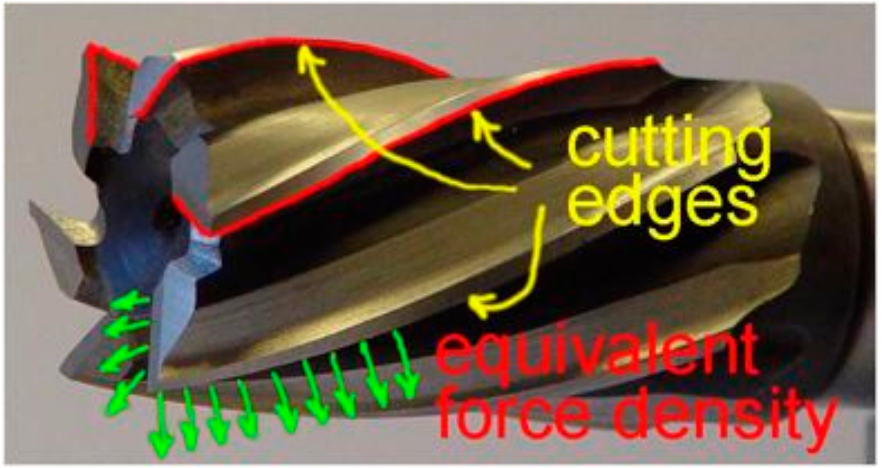


Cutting forces are deduced from:

- **instantaneous cutting conditions**
- **a <u>cutting law</u>**

Typical cutting law:

$$F_\alpha = K_\alpha \frac{b}{h_0}\left(\frac{h}{h_0}\right)^{n_\alpha}$$



Approaches at the macroscopic scales

Using CAD software to check "geometrically" the tool path for a chosen set of parameters

Test of the dynamic stability on an arbitrary chosen set of positions with associated assumptions

Test of the whole operation with minimum of assumptions: Full transient analysis

+ quick
- physical

+ physical
- slow

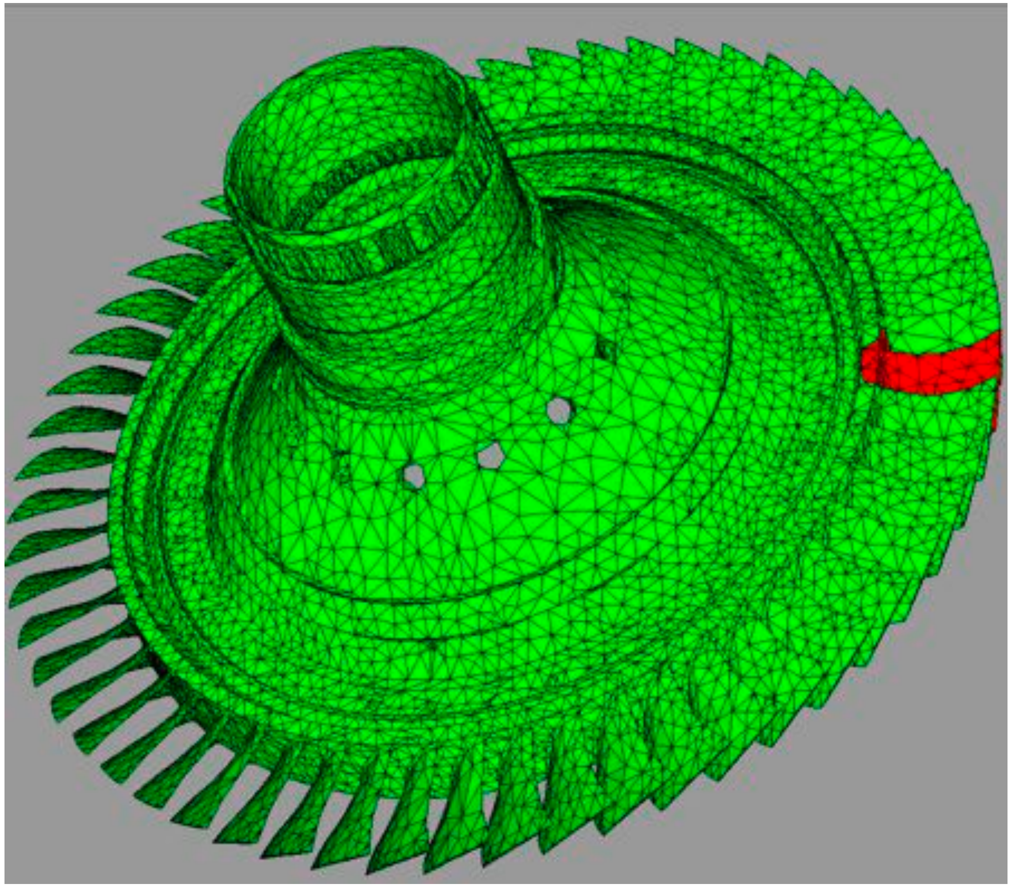
Analitycal stability criterion/ semi-discretization
Ismail, Soliman, Altintas, Budak, Stépan, Insperger, …

Full Time Domain
Biermann, Surmann, Coffignal & Lorong …

Flexible workpiece

A typical example: Blade milling *

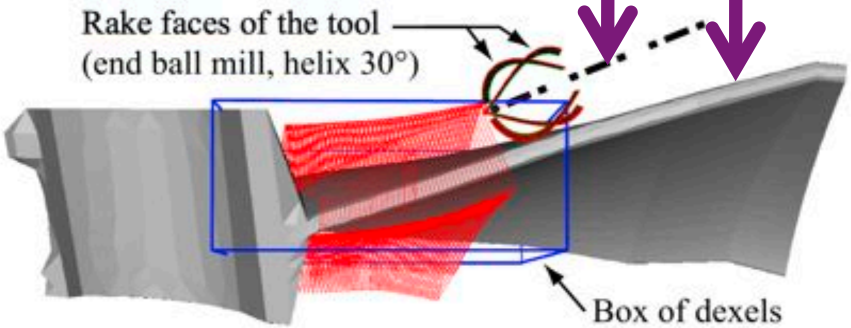
Bladed disc (blisc) : 56 blades



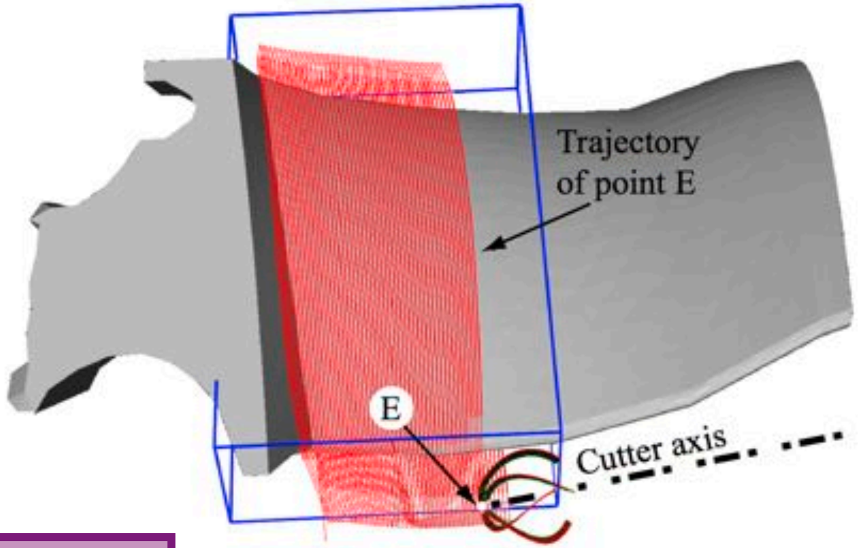
Tool and Workpiece may be flexible

Flexible workpiece

Flexible tool



(a) View 1: the blade and, on the right, the positions of the four rake faces of the end ball mill at the beginning of machining.

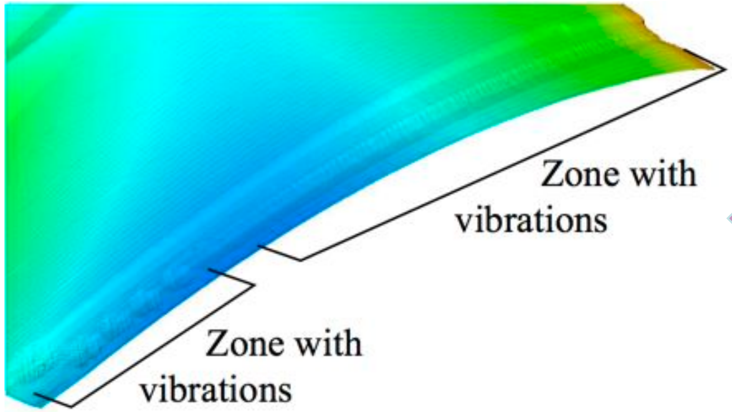


imposed trajectory of the center point of the cutter end E, and the positions of the four rake faces at $\tau = 0$.

Needed models

→ The FE cannot be used to model the mater erasing

Machined surface

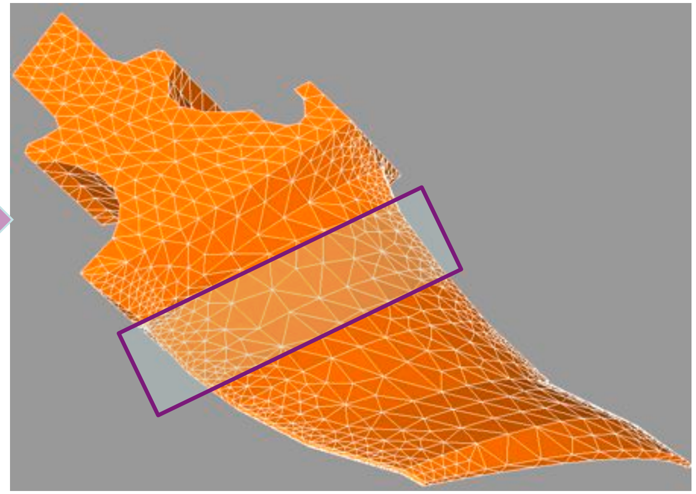


Geometric models:

- **Part (machined surface) : *Dexels***
- **Tool (erasing surface) : *Mesh***

Kinematic link

Flexible part & tool



Finite Elements models

Erasing tool

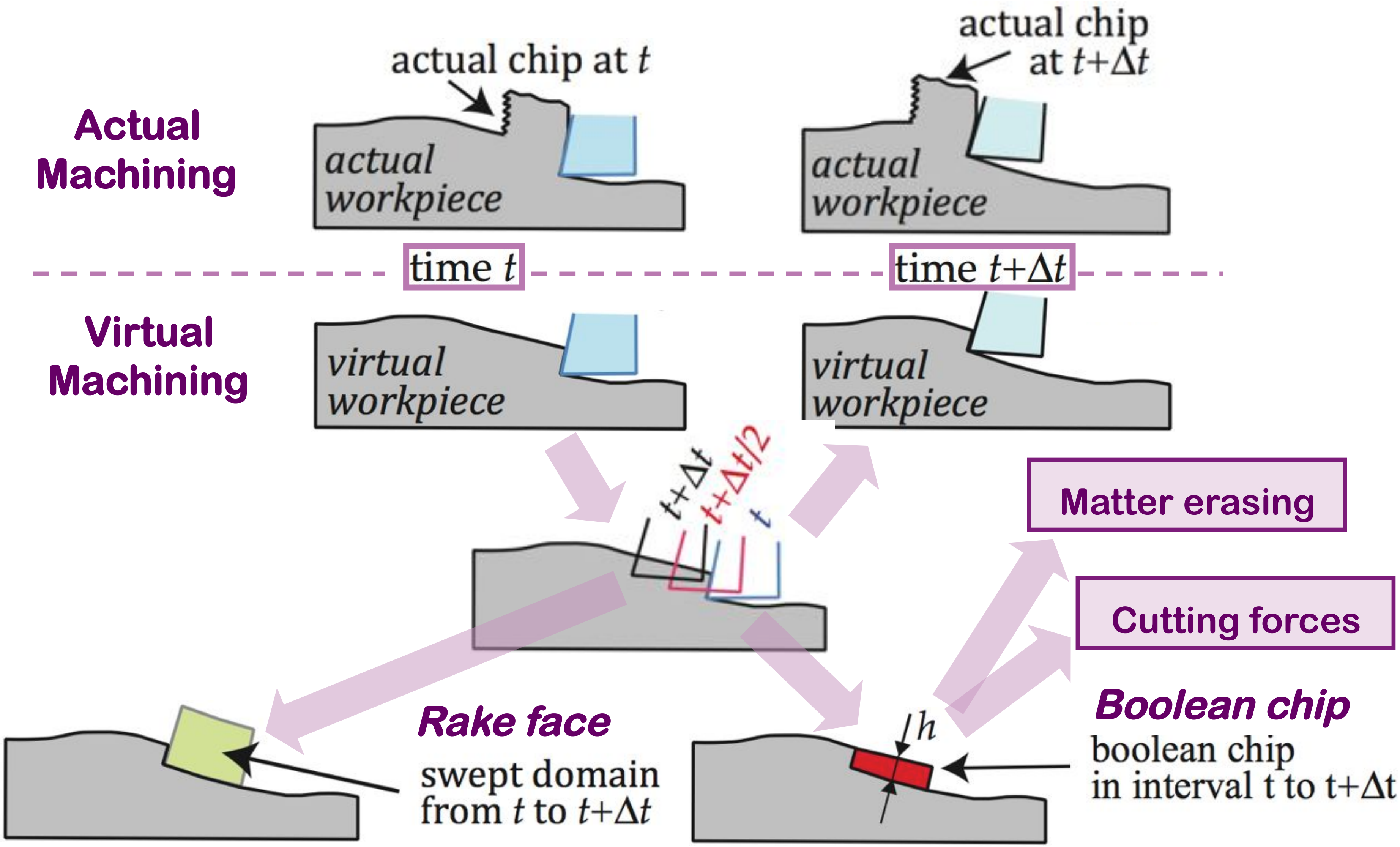
Matter erasing

Tool/Part Interaction

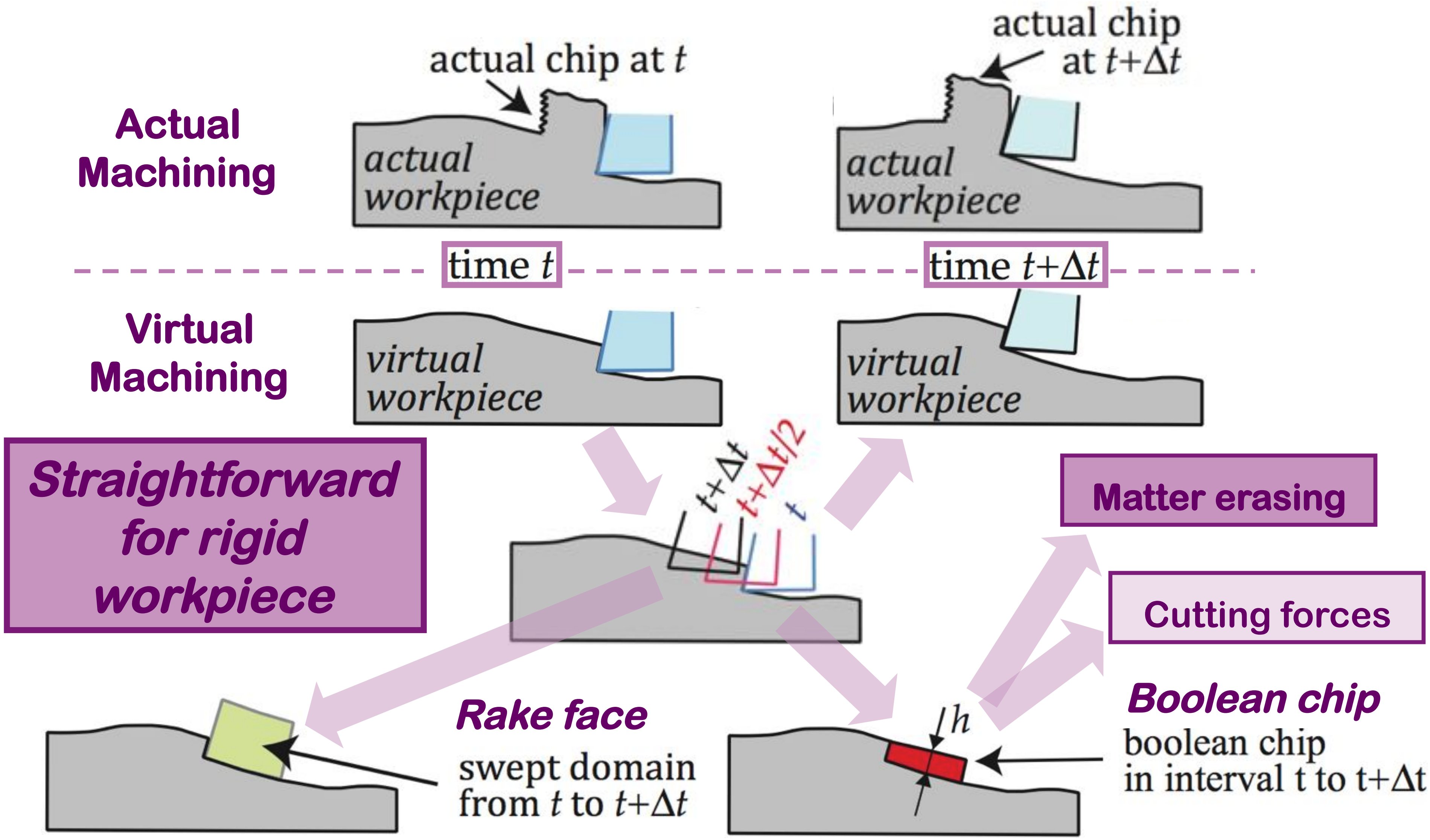
Cutting law

Cutting forces

Tool/Workpiece interaction – Rigid workpiece



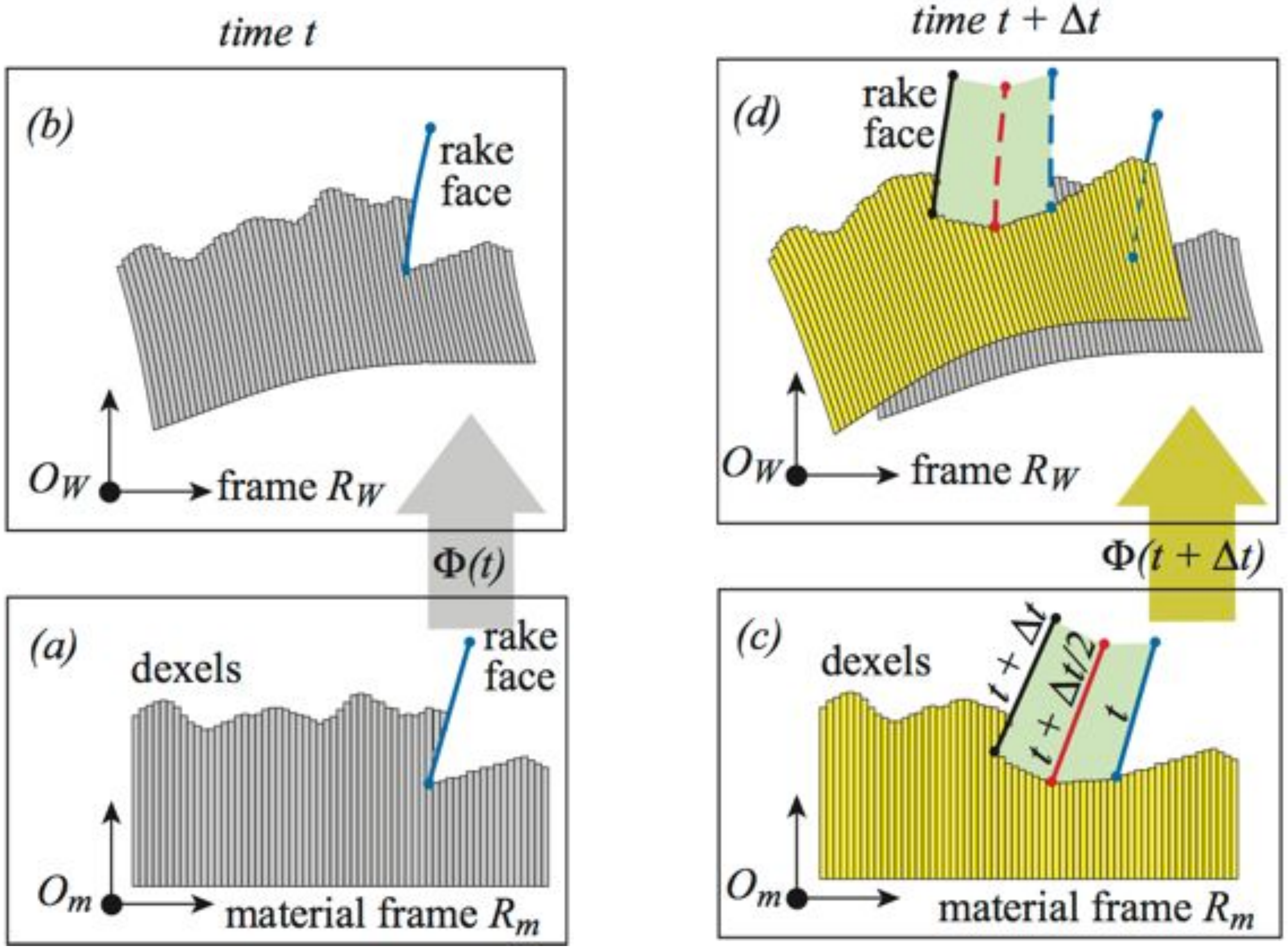
Tool/Workpiece interaction – Rigid workpiece



Tool/Workpiece interaction – Flexible workpiece

Shape of the workpiece in R_W

Shape of the workpiece in R_m



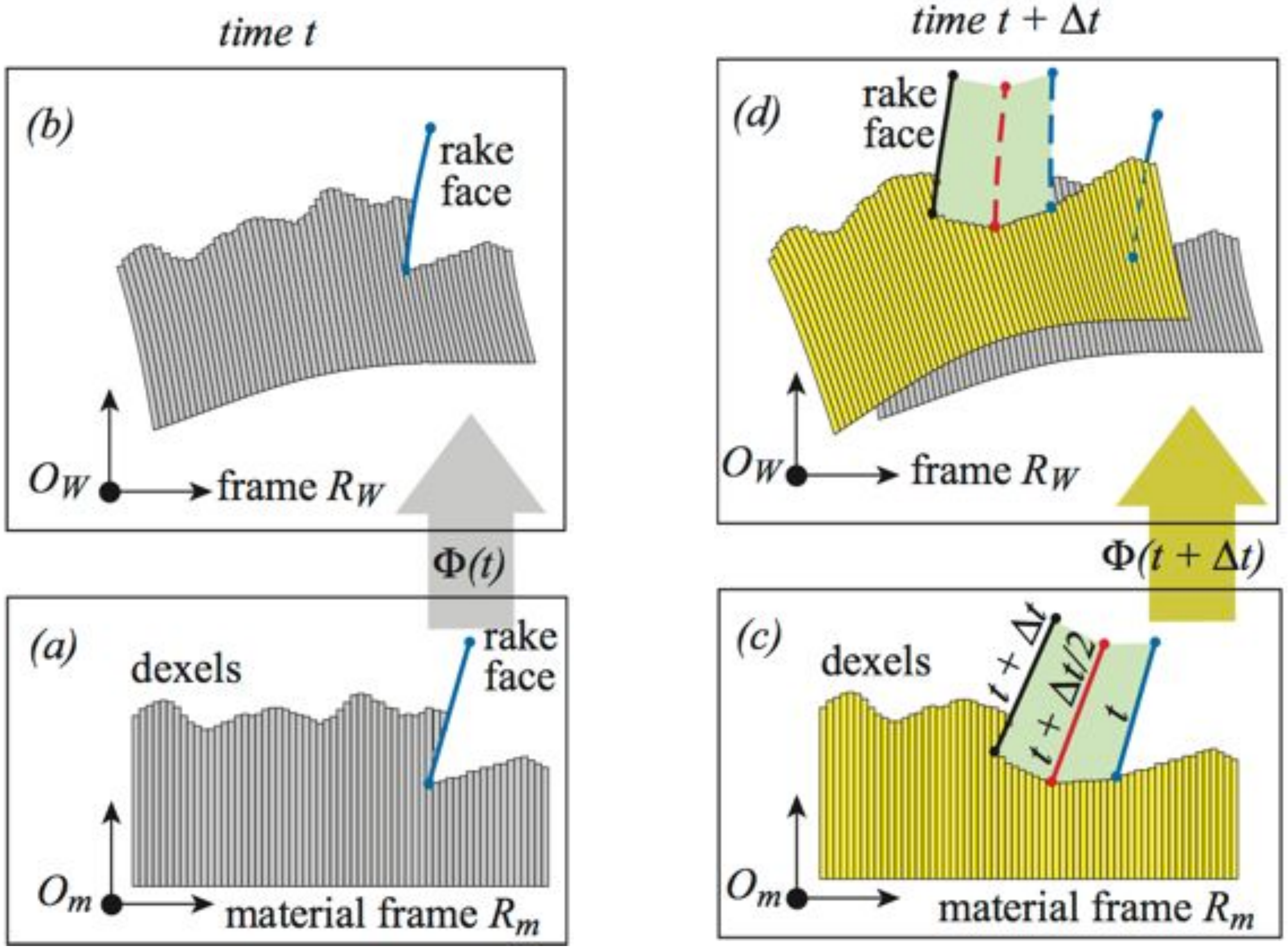
R_W **: frame where dynamic model of the workpiece is defined**

R_m **: *material* frame of the workpiece**

Tool/Workpiece interaction – Flexible workpiece

Shape of the workpiece in R_W

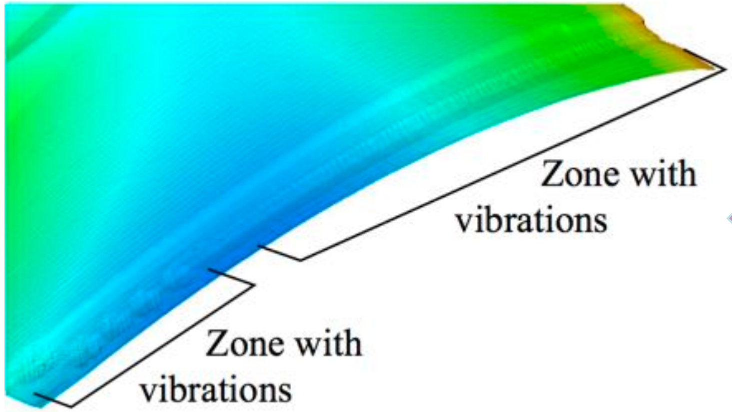
Shape of the workpiece in R_m



Matter erasing is conducted in the material frame R_m

Needed models

Machined surface

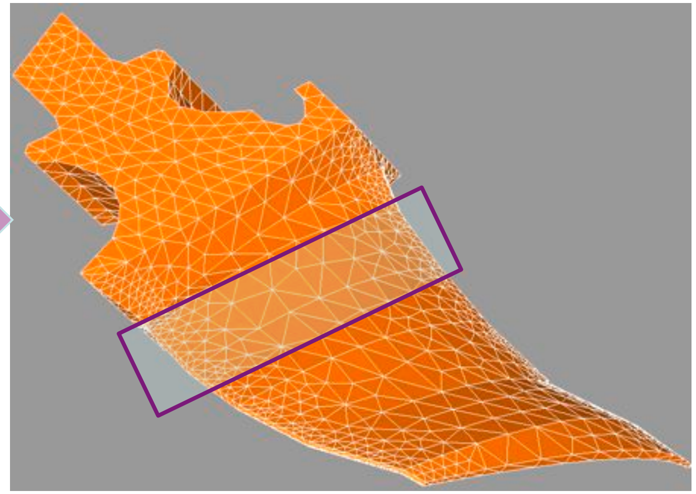


Geometric models:

- **Part (machined surface) :** ***Dexels***
- **Tool (erasing surface) :** ***Mesh***

Kinematic link

Flexible part & tool



Finite Elements models

Erasing tool

Matter erasing

Tool/Part Interaction

Cutting law

Cutting forces

Blisc Flexible part &tool: Finite Elements Models

The workpiece

Simulations with a single blade:

- Quadratic tetrahedrons

→ first 10 mode shapes

Simulation with the whole Blisc:

- Quadratic tetrahedrons + cyclic symmetry

→ first 180 mode shapes

The tool

→ A Simple beam (rake faces having a rigid motion)

Cutting forces

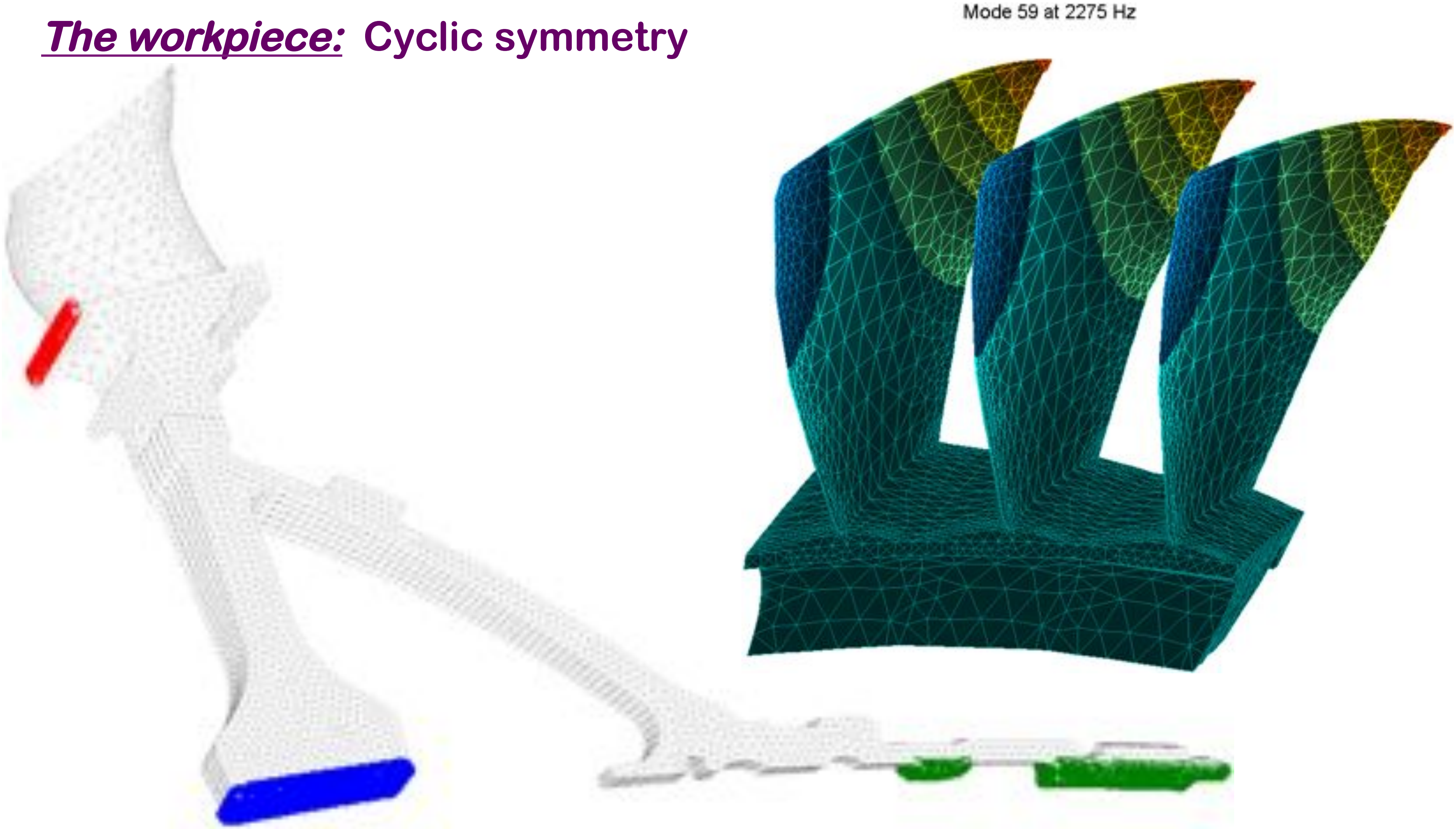
$$\begin{cases} [M]_T.\{\ddot{q}\}_T + [\tilde{D}]_T.\{\dot{q}\}_T + [\tilde{K}]_T.\{q\}_T = \{Q\}_T + \{Q\}_{W/T} \\ [M]_W.\{\ddot{q}\}_W + [\tilde{D}]_W.\{\dot{q}\}_W + [\tilde{K}]_W.\{q\}_W = \{Q\}_W + \{Q\}_{T/W} \end{cases}$$

Include non Galilean effects (rotations,...)

A modal reduction is used

Flexible part: Finite Elements Model

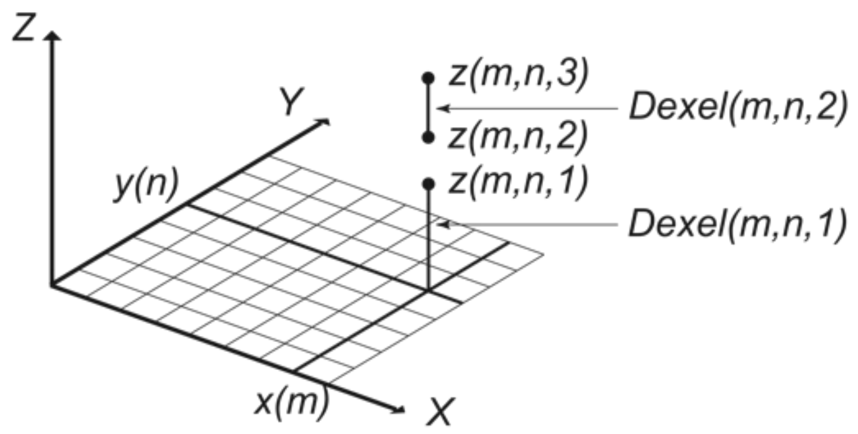
The workpiece: Cyclic symmetry



Modelling: SDT (Structural Dynamic Toolbox)

Geometric model of the machined area

Dexel-based volume representation (multi-level Z-Map model*)



Fine (but non homogeneous)

➡ **Necessary to describe the matter erasing and cutting forces**

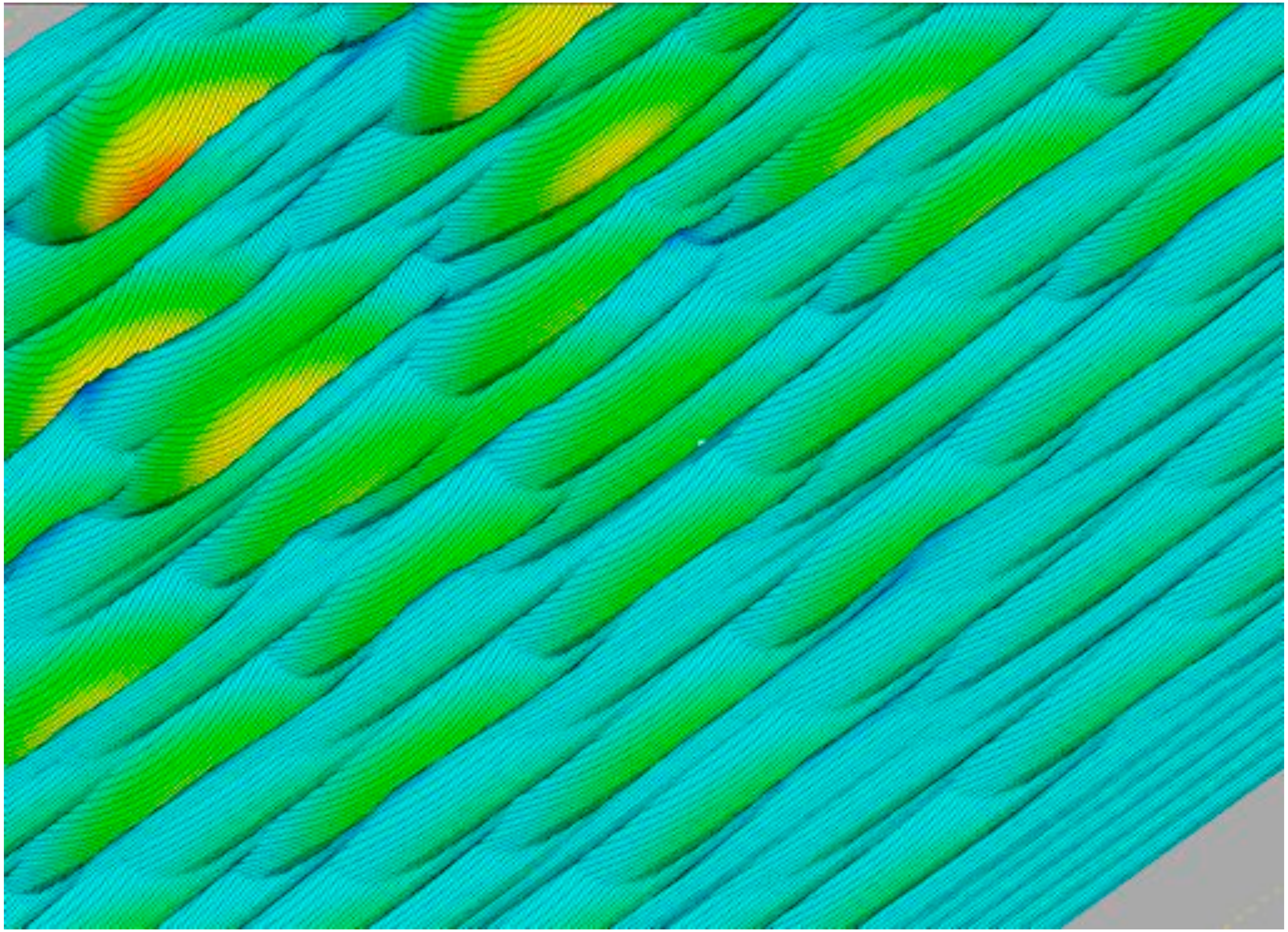
Intersection algorithms are robust

➡ **Necessary for the Time Domain approach (nb Time steps ~ 10^6)**

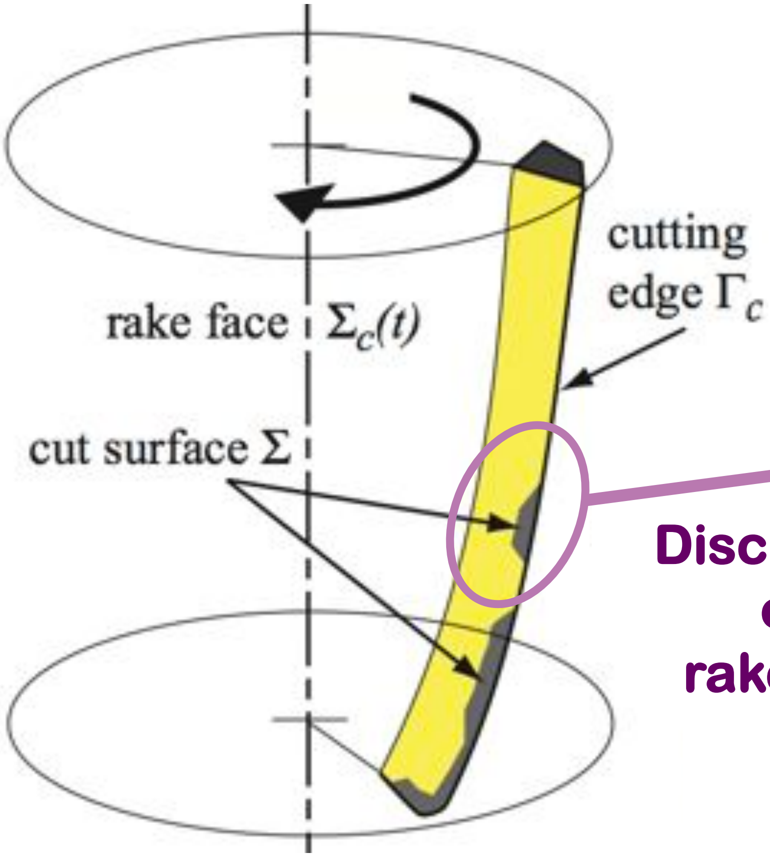
* B.K. Choi and R.B. Jerard

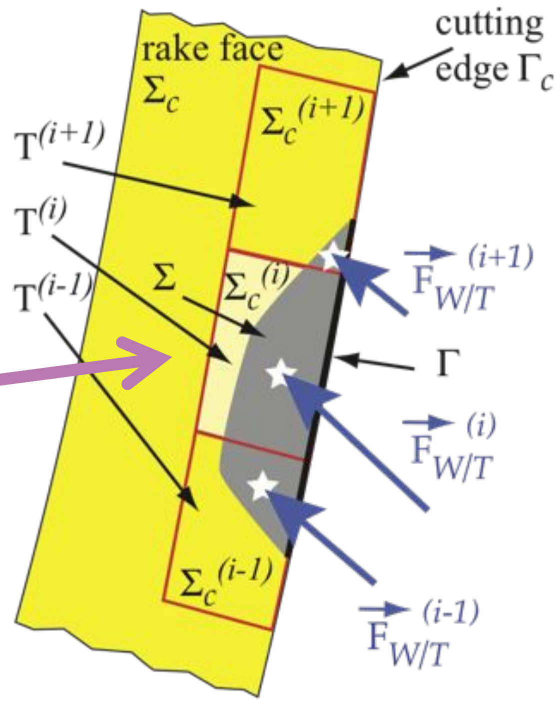
Geometric model of the machined area

Example of a machined surface describes with dexels (20 000 000)



Tool/Part interaction: Cutting forces – Cutting law



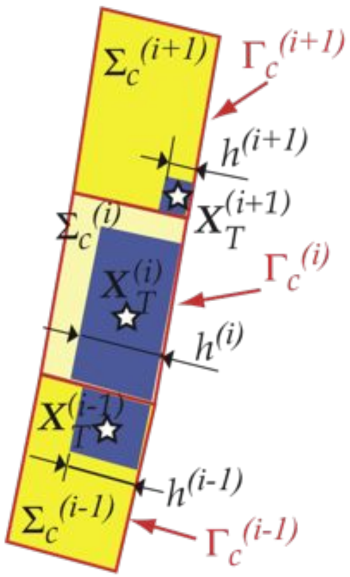


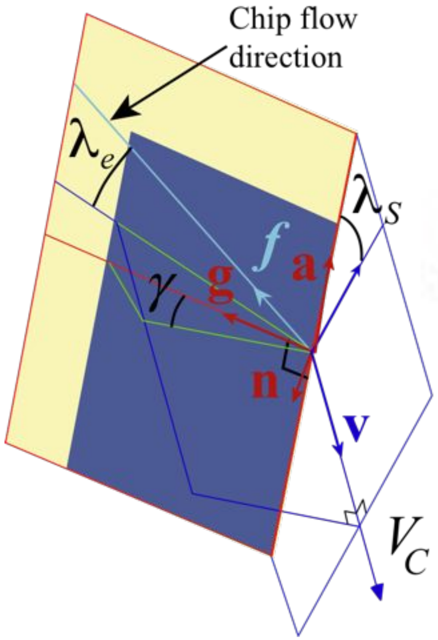
Discretization of the rakes faces

Elementary tools → **Elementary cutting forces**

Tool/Part interaction: Cutting forces

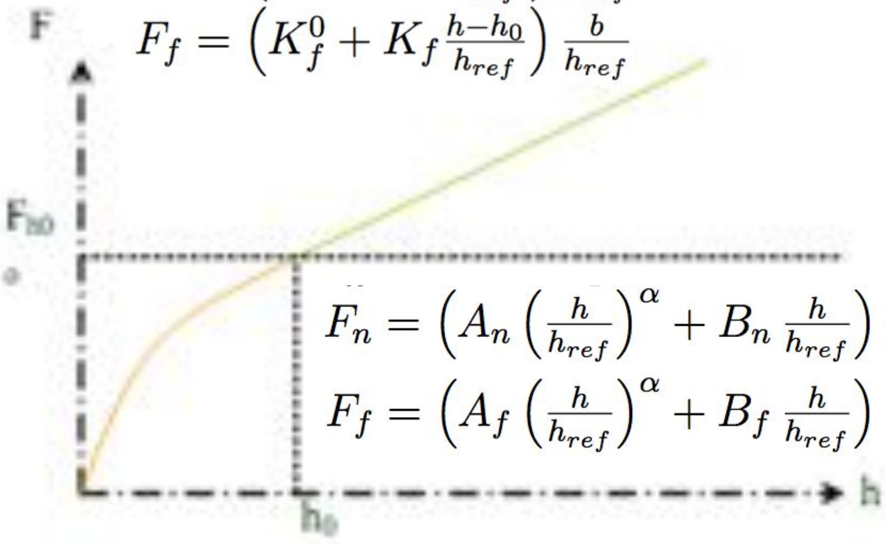
Elementary cutting forces ← Cutting law*





$$\lambda_e = K_{\lambda_e} . \lambda_s$$

$$F_n = \left(K_n^0 + K_n \frac{h-h_0}{h_{ref}}\right) \frac{b}{h_{ref}}$$
$$F_f = \left(K_f^0 + K_f \frac{h-h_0}{h_{ref}}\right) \frac{b}{h_{ref}}$$



$$F_n = \left(A_n \left(\frac{h}{h_{ref}}\right)^{\alpha} + B_n \frac{h}{h_{ref}}\right) \frac{b}{h_{ref}}$$
$$F_f = \left(A_f \left(\frac{h}{h_{ref}}\right)^{\alpha} + B_f \frac{h}{h_{ref}}\right) \frac{b}{h_{ref}}$$

$$A_n = \frac{K_n^0 - \frac{h_0}{h_{ref}} K_n}{(1-\alpha)\left(\frac{h_0}{h_{ref}}\right)^{\alpha}} \quad B_n = K_n - \alpha \left(\frac{h_0}{h_{ref}}\right)^{\alpha-1} A_n$$

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*N. Corduan, PHD

Headlines of the Algorithm

Dynamic non linear time domain approach

Newmark Incremental Scheme
+ Newton Iterations Scheme for each time-step

On an increment (from t to $t+\Delta t$)

- ***For each iteration:***

1. Calculation of the Cutting forces

Intersection between :
- *actual domain* occupied by the workpiece
- *swept volume* generated by the rake faces over *the increment*

2. Evaluation of the dynamical balance

- ***When the Newton scheme has converged:***

Updating of the Workpiece Geometry Model

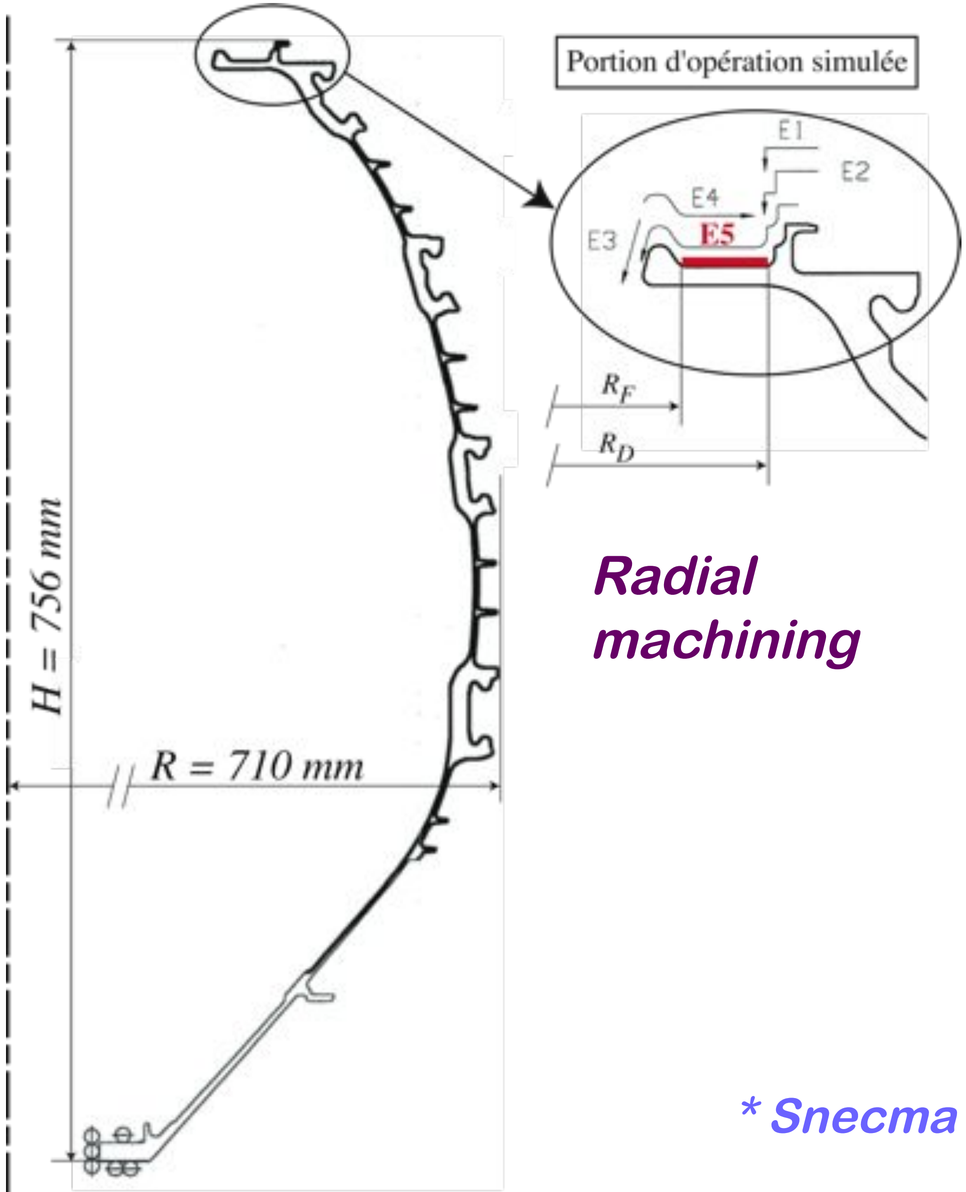
The numerical cost is mainly due to the intersection calculations

Turning example: Drum (turbofan GE90 engine)*

FE model of the Drum

• expensive part
• lack of experimental data

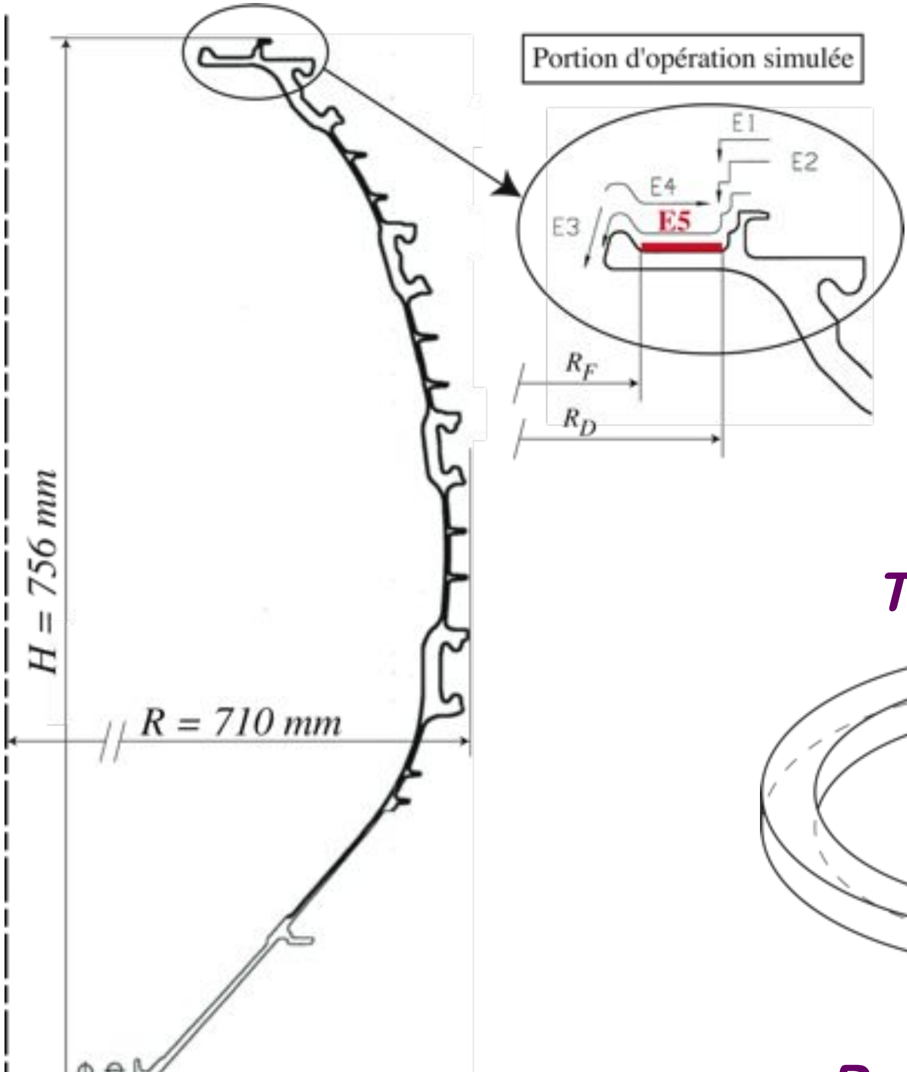
Development of a laboratory experiment



Radial machining

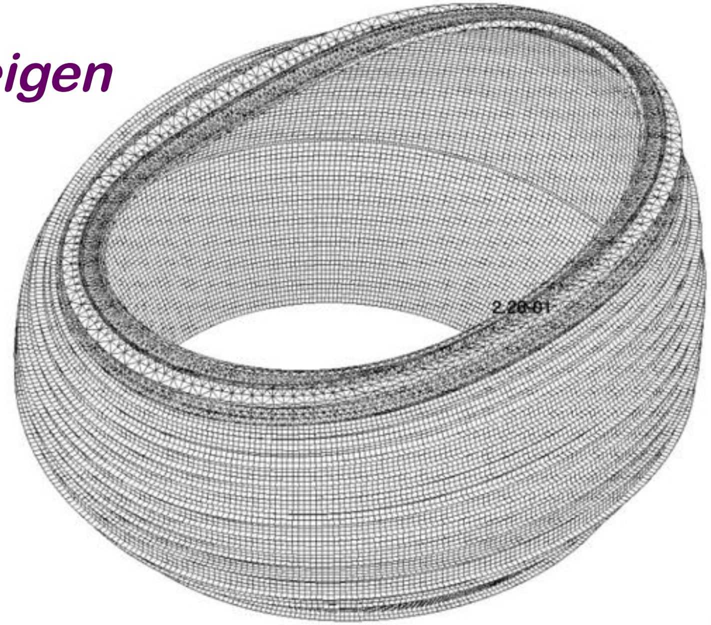
** Snecma*

Back to the drum (turbofan GE90 engine)*

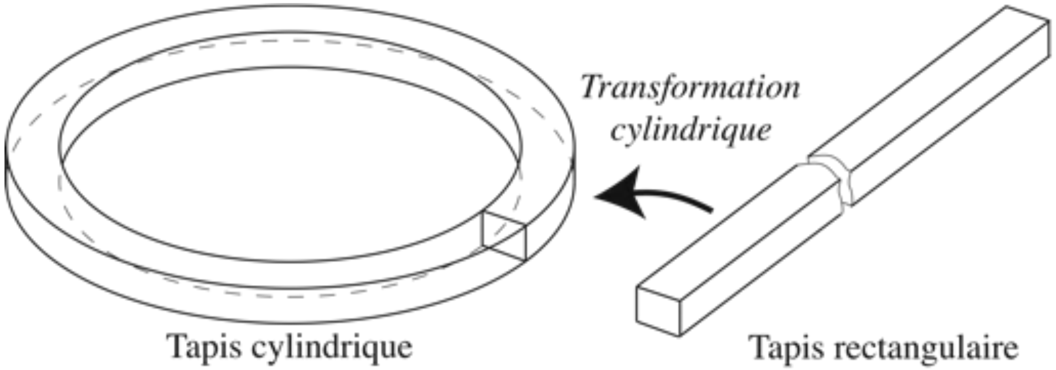


*Snecma

First eigen mode



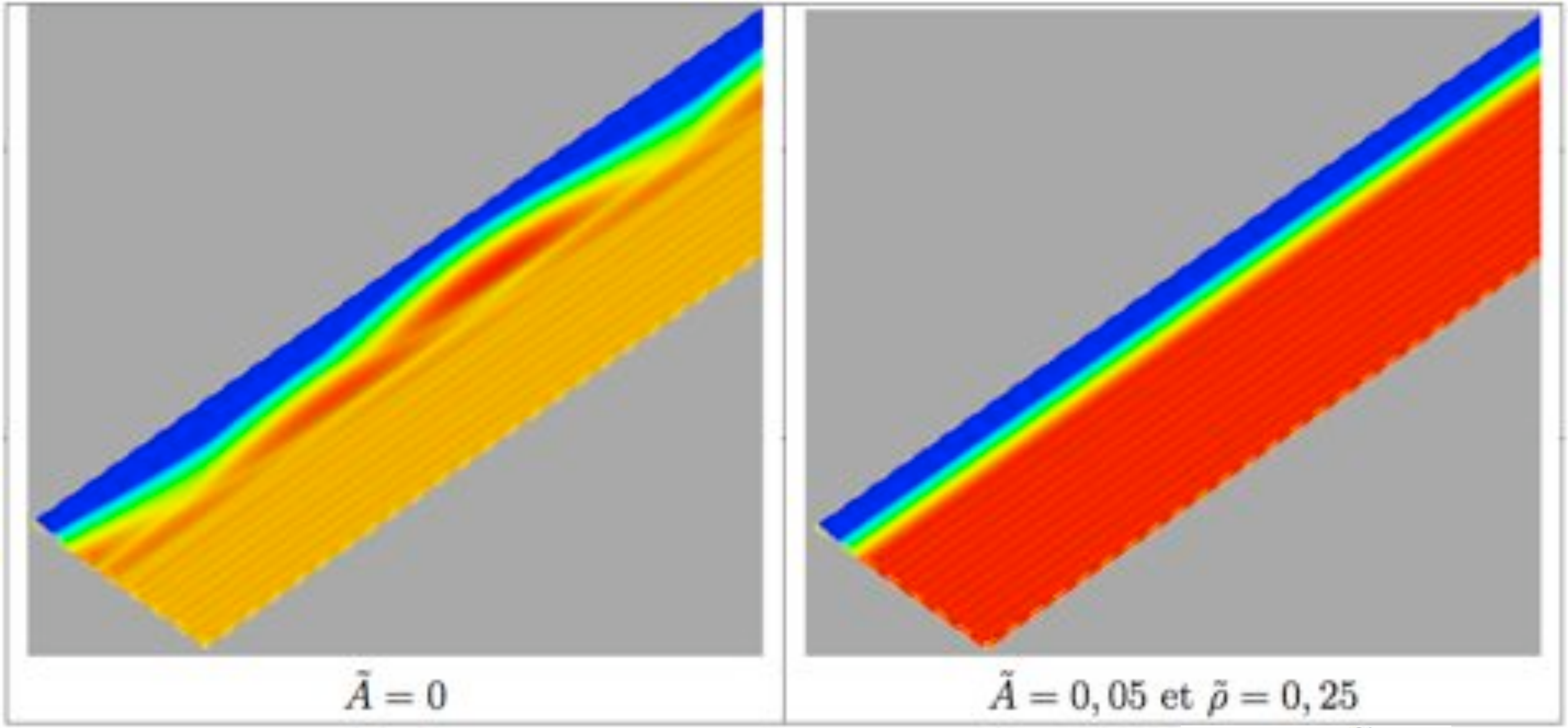
Transformation of the dexel carpet



Dexels are put in the axial direction

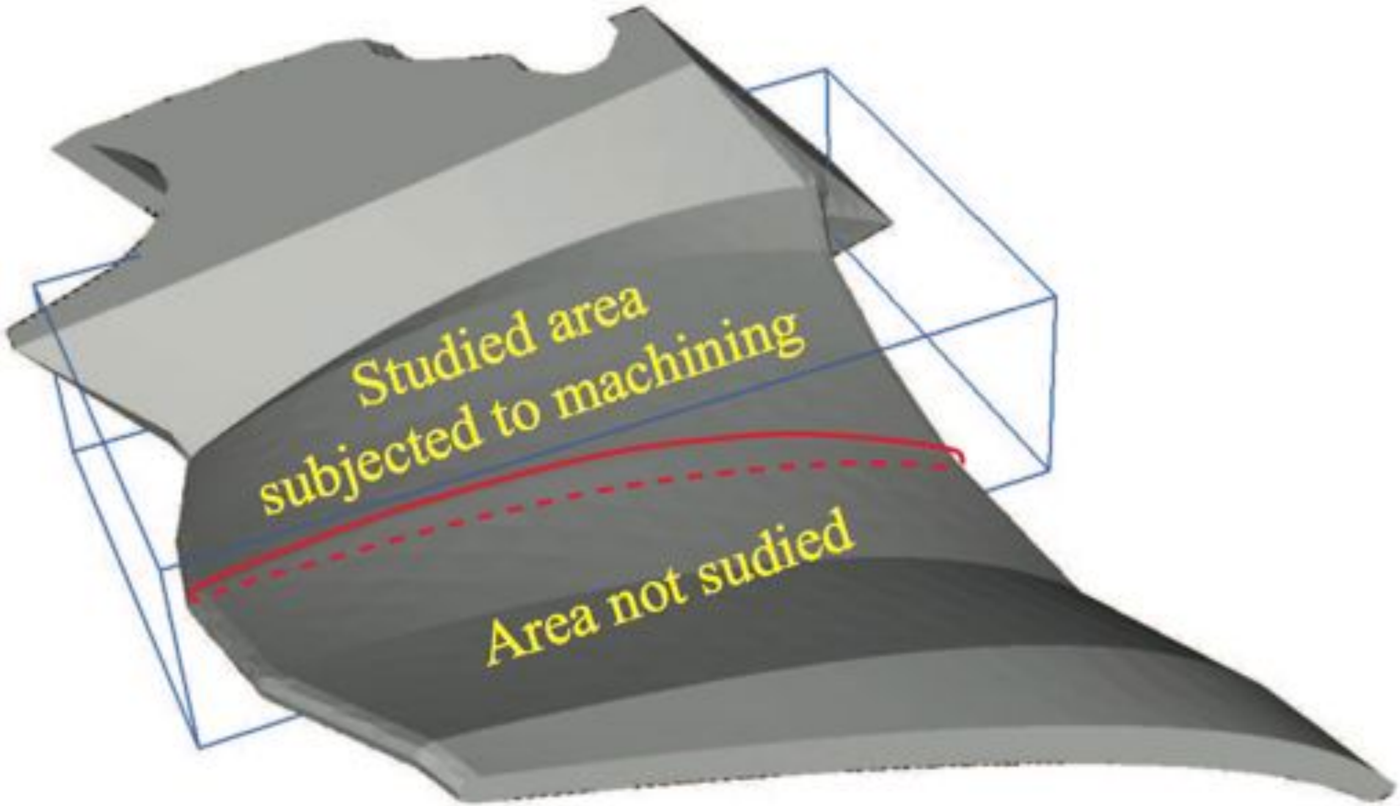
Back to the drum (turbofan GE90 engine)*

Effect of the modulation of the cutting speed



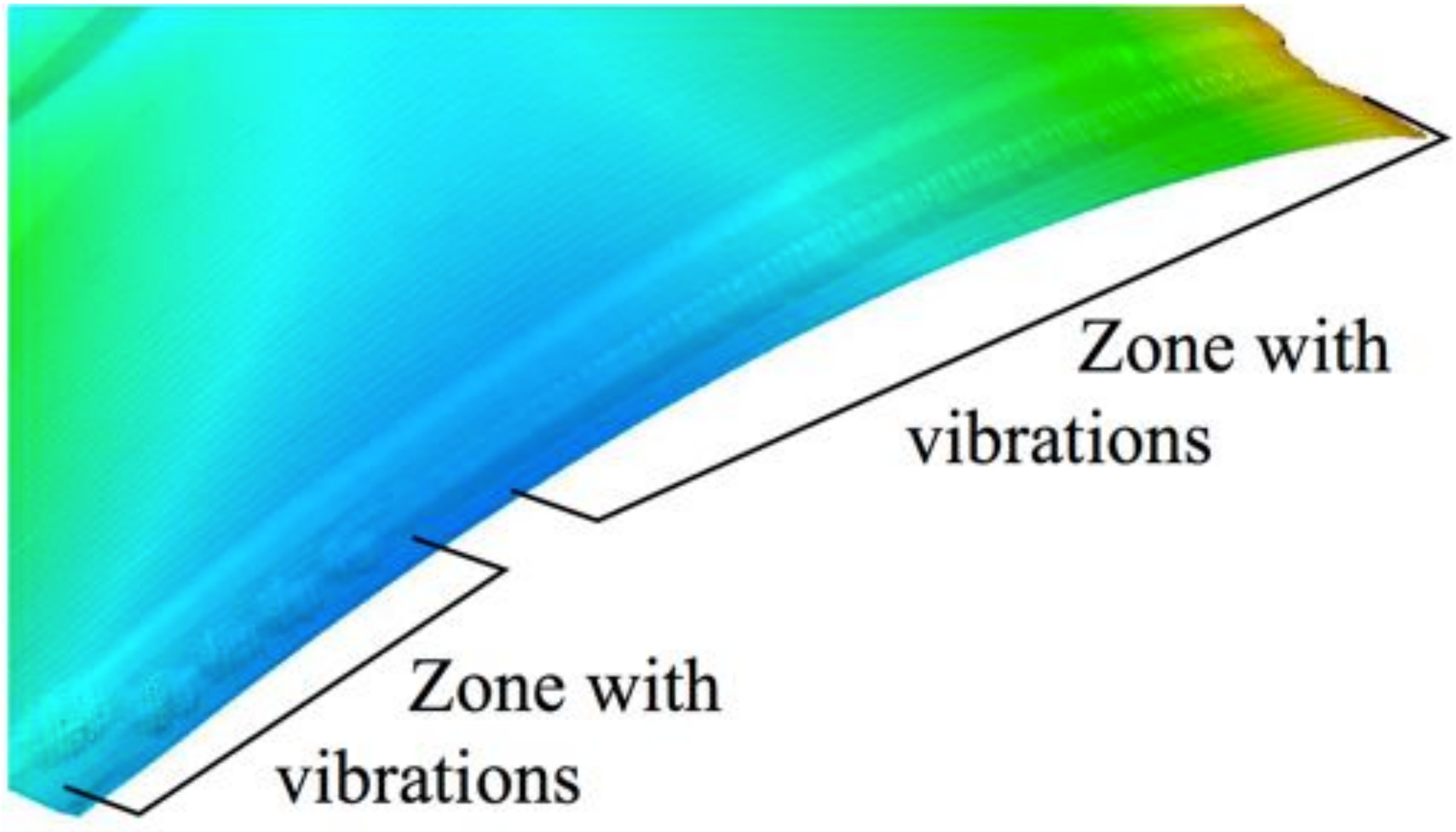
$\tau = 0,44\%$ $\quad \tilde{V}_c(t) = V_c * \left[1 + \tilde{A} * \sin(\tilde{\omega} t)\right] \quad \tilde{\rho} = \dfrac{\tilde{\omega}}{\omega_{broche}}$

Blisc simulation results



Difficulty: We do not have data for the damping of the tool nor the worpiece

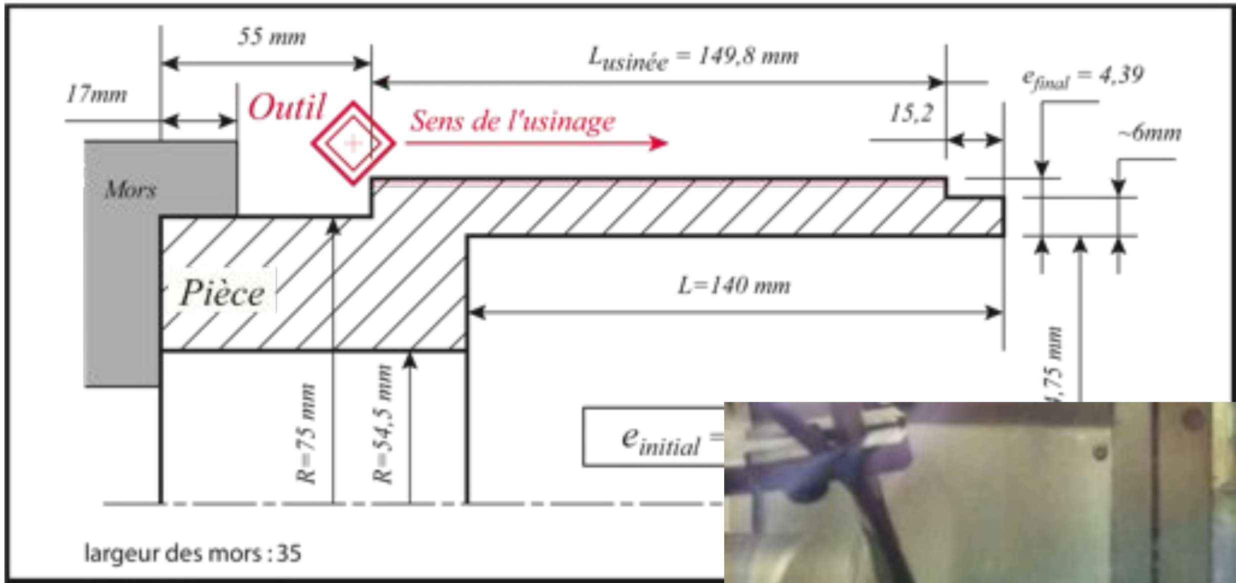
Simulation results



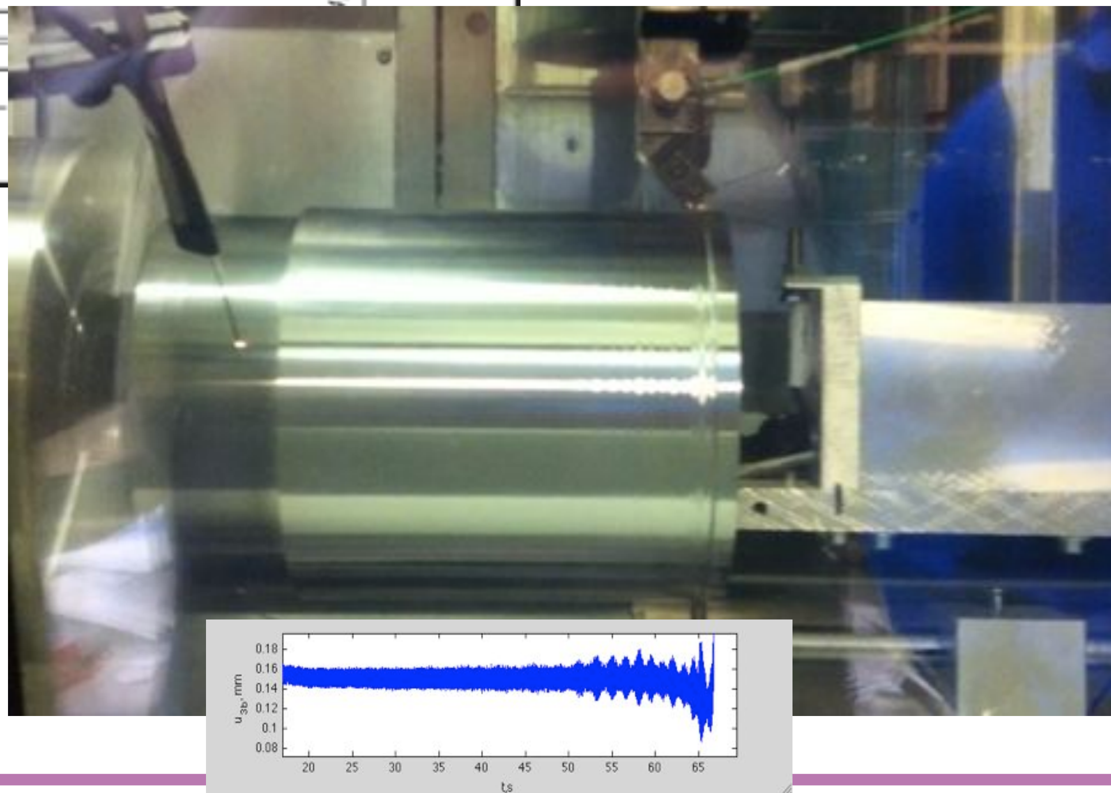
(a) ($\xi_W = 0.003$, $\xi_T = 0.01$)

Flexible Workpiece
Rigid Tool

Axial machining of a tube



The part is the only weak component

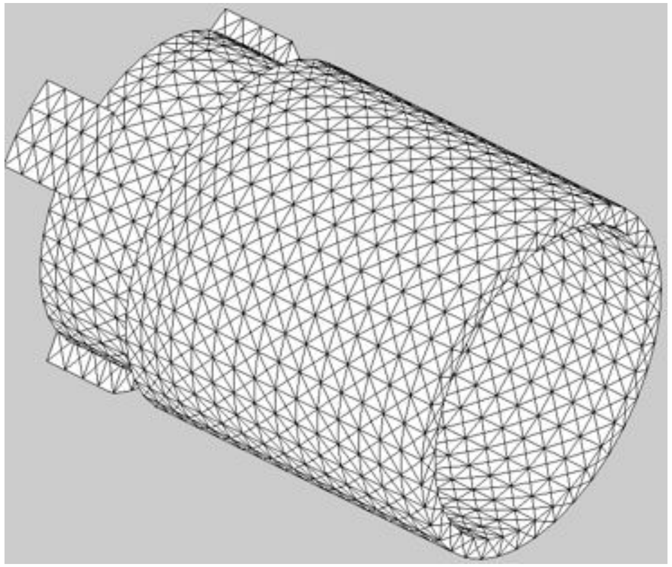


- Regular evolution of the local stiffness

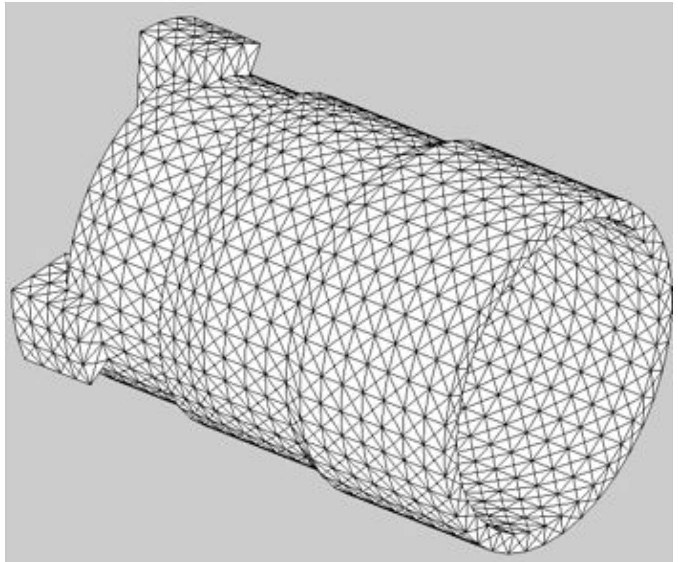
Chatter occurs during the machining

Dynamic model of the tube

The variation of the tube section is take into account with an adaptive finite element mesh



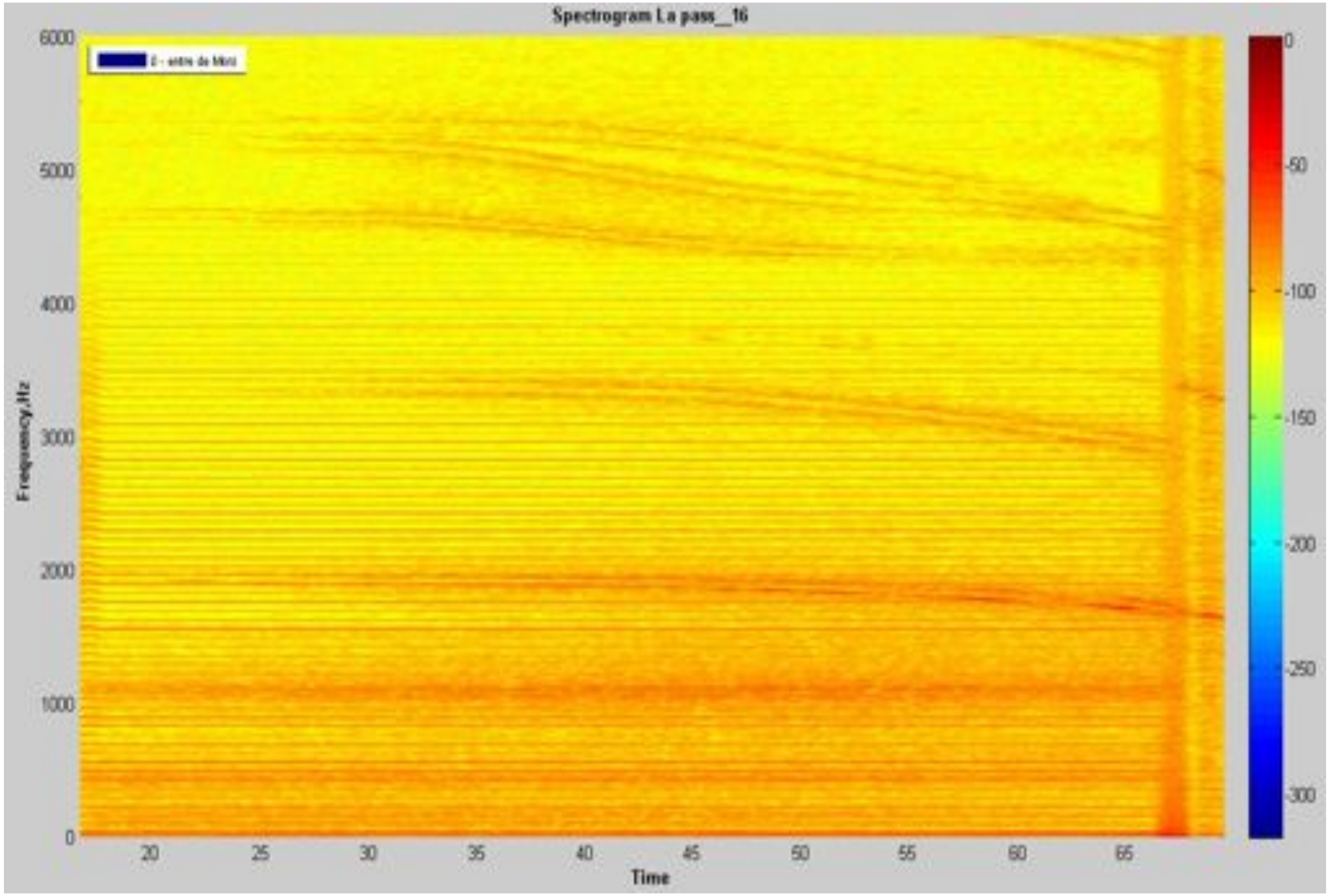
Tube before machining



Tube during machining
(tool position: 80 mm)

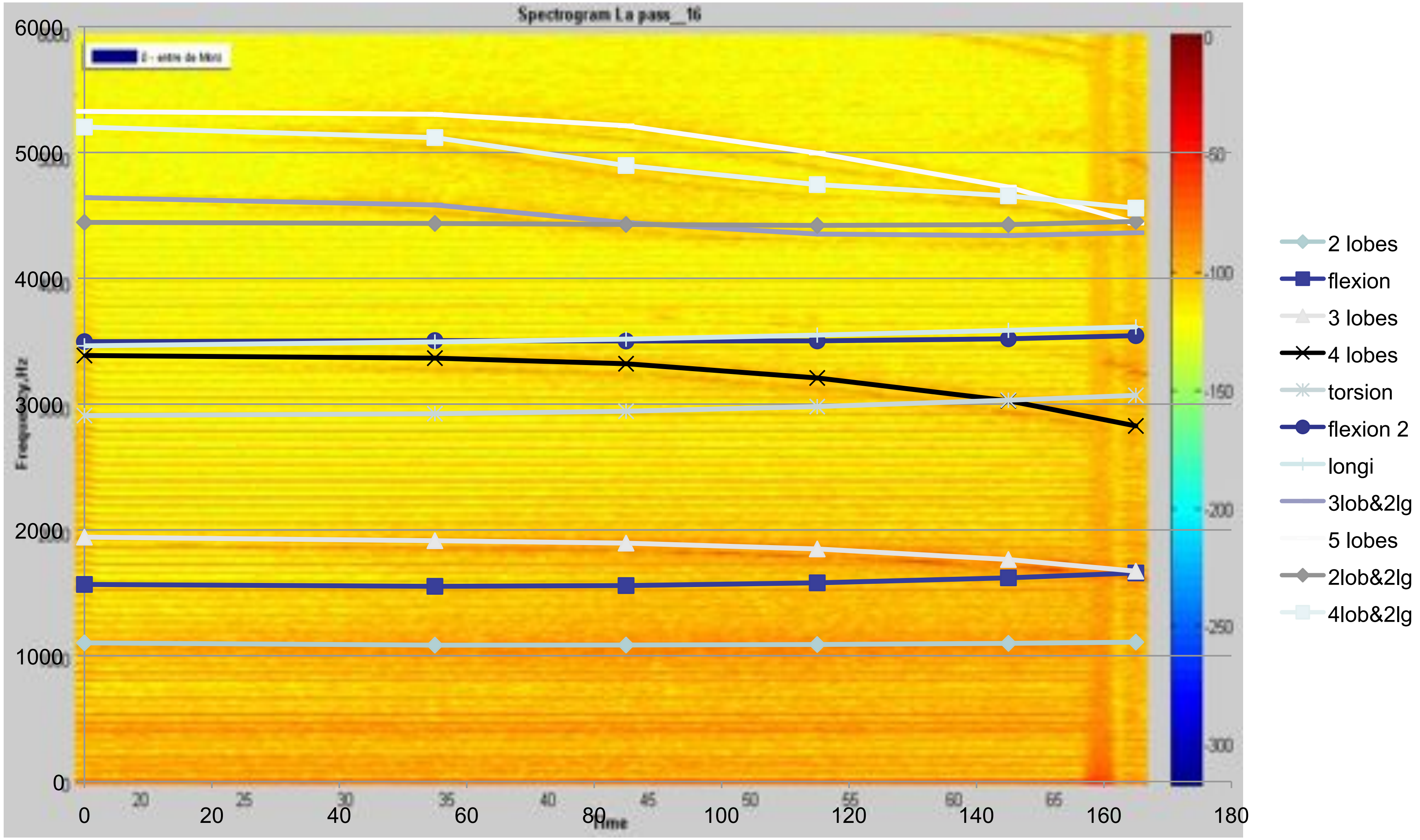
Finite Element code: OpenFEM + SDT

Dynamic behaviour of the tube: Experimental results



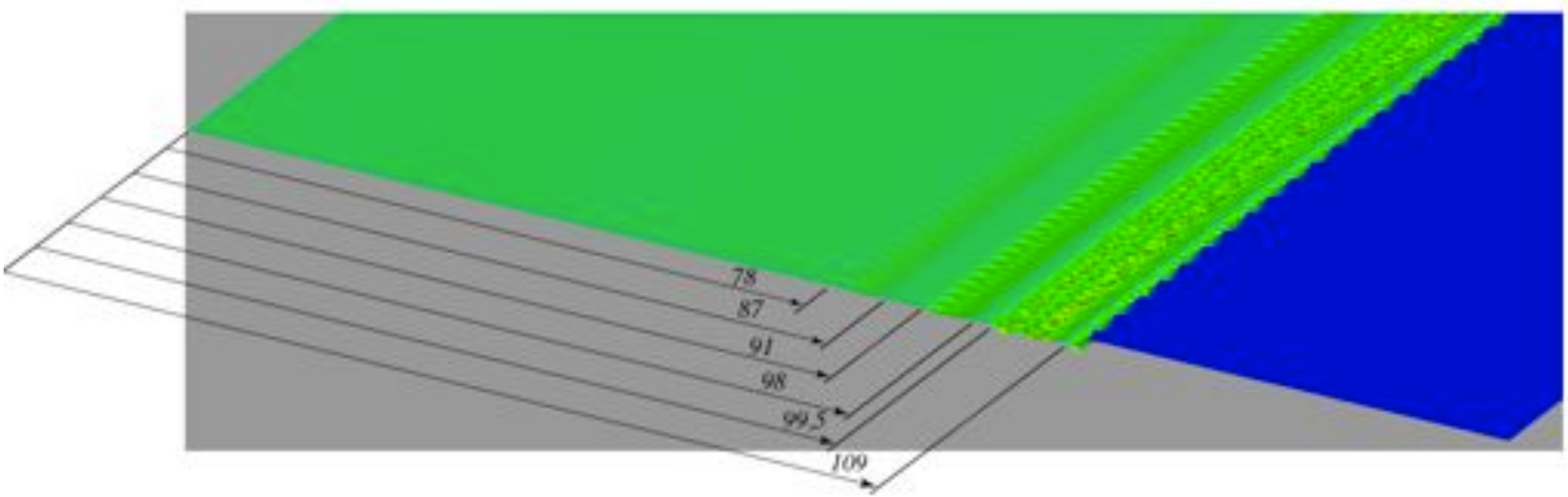
Spectrogram

Dynamic behaviour of the tube: Experimental results



Spectrogram

Simulations with evolution of the mechanical behaviour



Experimental	***Simulation***
1st bifurcation: 90 mm	**1st bifurcation: 78 mm**
2nd bifurcation: 100 mm	**2nd bifurcation : 87mm**

→ Different vibrating zones are obtained with the time domain approach

→ Ploughing is not take into account

Conclusion – Macroscopic scale

Remarks on the Time Domain approach

- Results are encouraging
- Ability to deals with industrial workpieces
- Few limitation for the improvement of the models (with highly non-linear aspects)
- Today damping modelling can only be based on measurements

Tracks to improve the results for the tube's machining simulation

- Take into account mass et stiffness evolution during machining
- Include gyroscopic effects
- Improve the cutting law (specially for small cutting thicknesses)
- Take into account the attachment
- Ploughing effect is a key point to have a realistic machining simulation for very thin workpieces

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Research at PiMM Laboratory

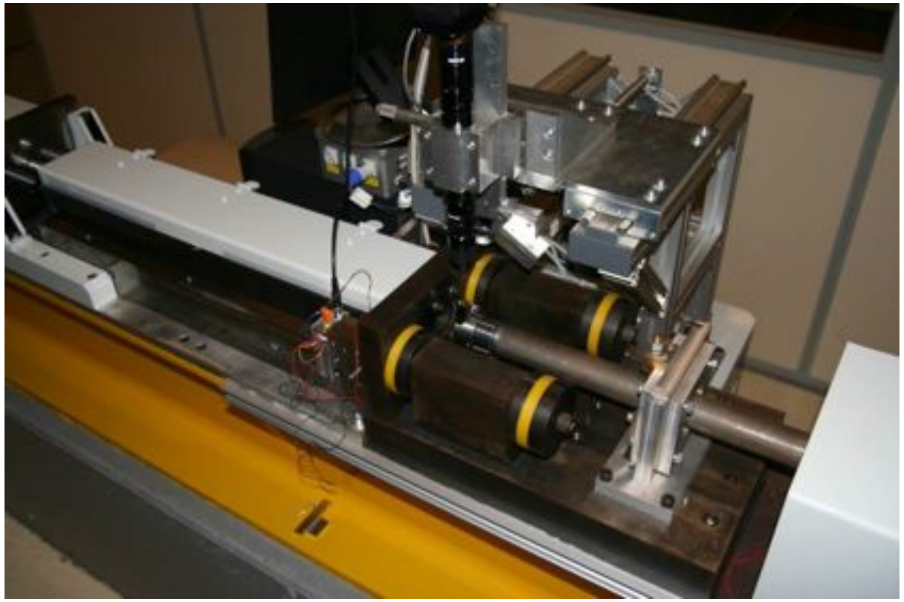
Milling / Turning

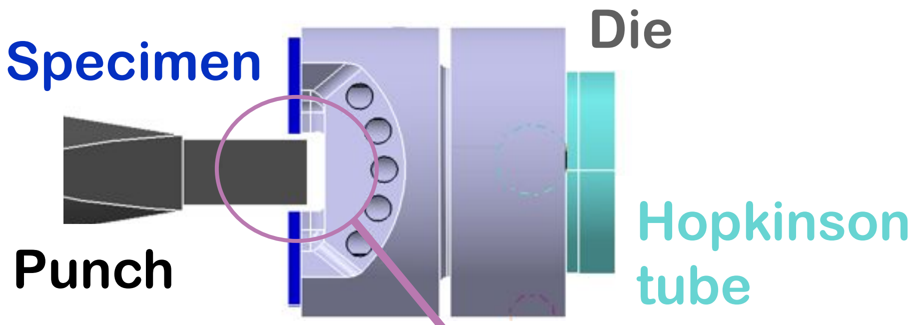
Flexible Part

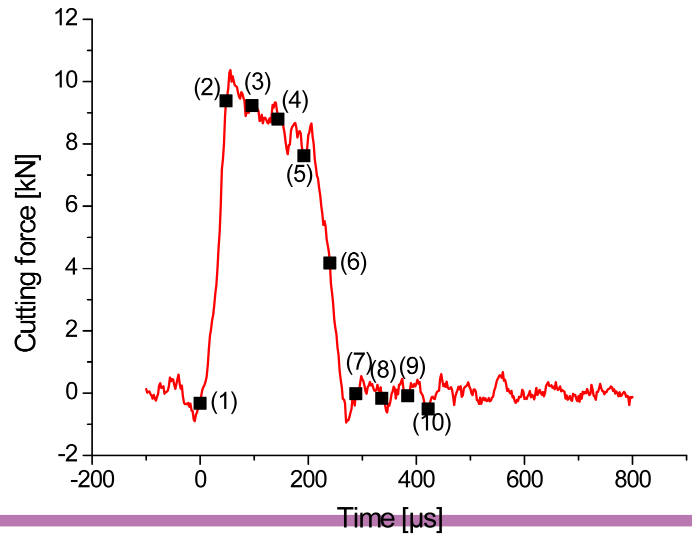
Blanking / Cutting

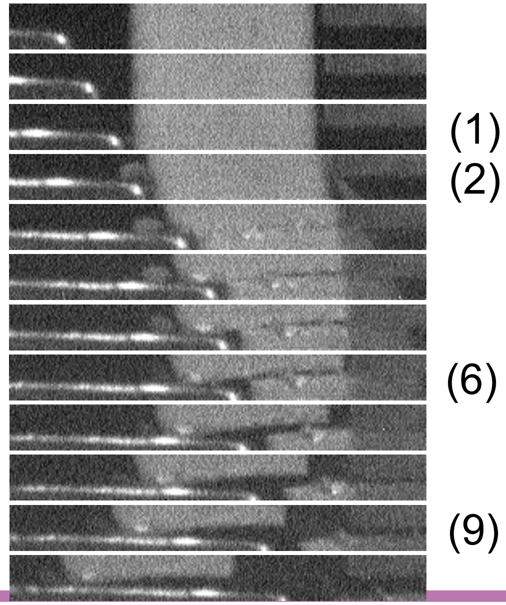
C-Nem

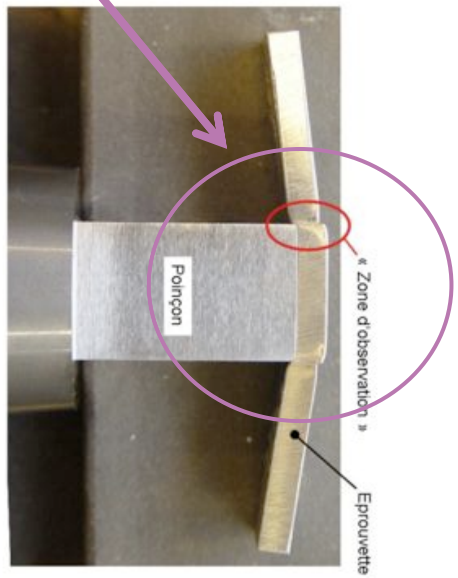
Mesoscopic Scale : High speed blanking Setup











Mesoscopic scale : Main difficulties

Behaviour modelling

- Constitutive law for Large strain + Large strain rates + Large temperature variation
- Tool/mater interface : High pressure / Small area / High relative speed
  - heat flux repartition ?

Handling Large strains + Large displacements

- Lagrangian FE approaches

  Difficulties : need a regularly remeshing (and data projections)

  → Not easy in 3D for complex geometries (robustness)
- Eulerian FE approaches

  Difficulty : boundary geometry evolution → Continuous chip only
- Arbitrary Lagrangian Eulerian approaches

  Difficulty : how to handle grid motion for Large displacement and strains

We propose to use a new approach : the CNEM

Constrained Natural Element Method : between Meshless and FE approaches

The CNEM

Main principle : **Galerkin approach base on the *Natural Neighbors interpolant* using a *Voronoi diagram* (Delaunay's dual)**

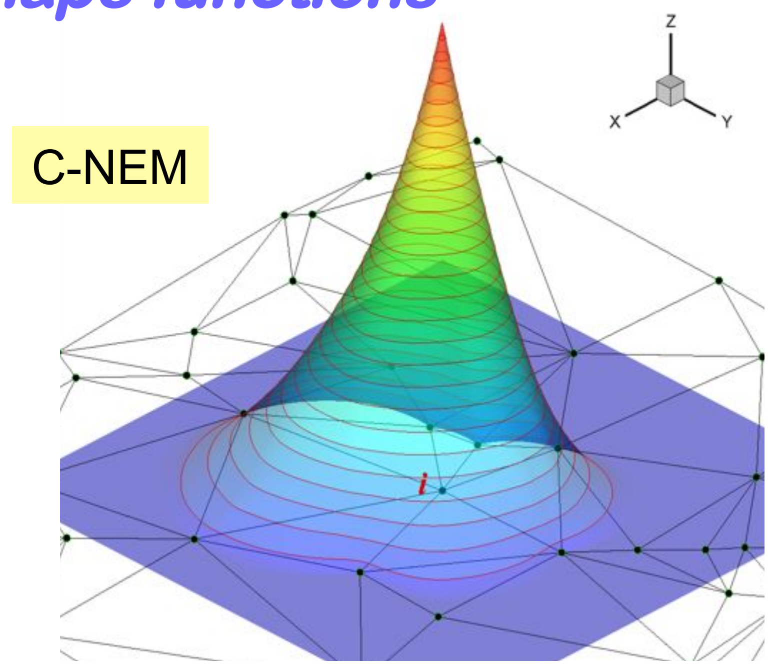
$$\mathbf{u}^{\mathbf{h}}(\mathbf{x}) = \sum_{i=1}^{n} \phi_i(\mathbf{x})\mathbf{u}_i$$

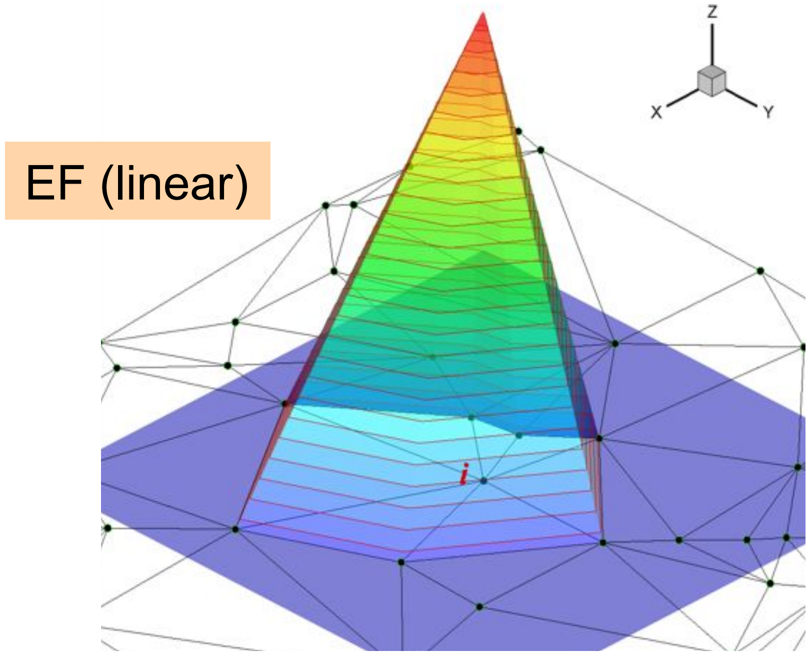
NEM (Sambridge)
Convex domain

CNEM (Chinesta, Illoul, Yvonnet, Lorong)
Non* convex domain : *Constrained Voronoi diagram

- **Cloud of nodes**
- **Domain boundary description (tesselation)**

Shape functions





Interpolation properties

- Nodale interpolation:

$$\phi_i(\mathbf{x}_j) = \delta_{ij}$$

- Partition of the unity:

$$\sum_{i=1}^{n} \phi_i(\mathbf{x}) = 1 \ \forall \mathbf{x} \in \Omega$$

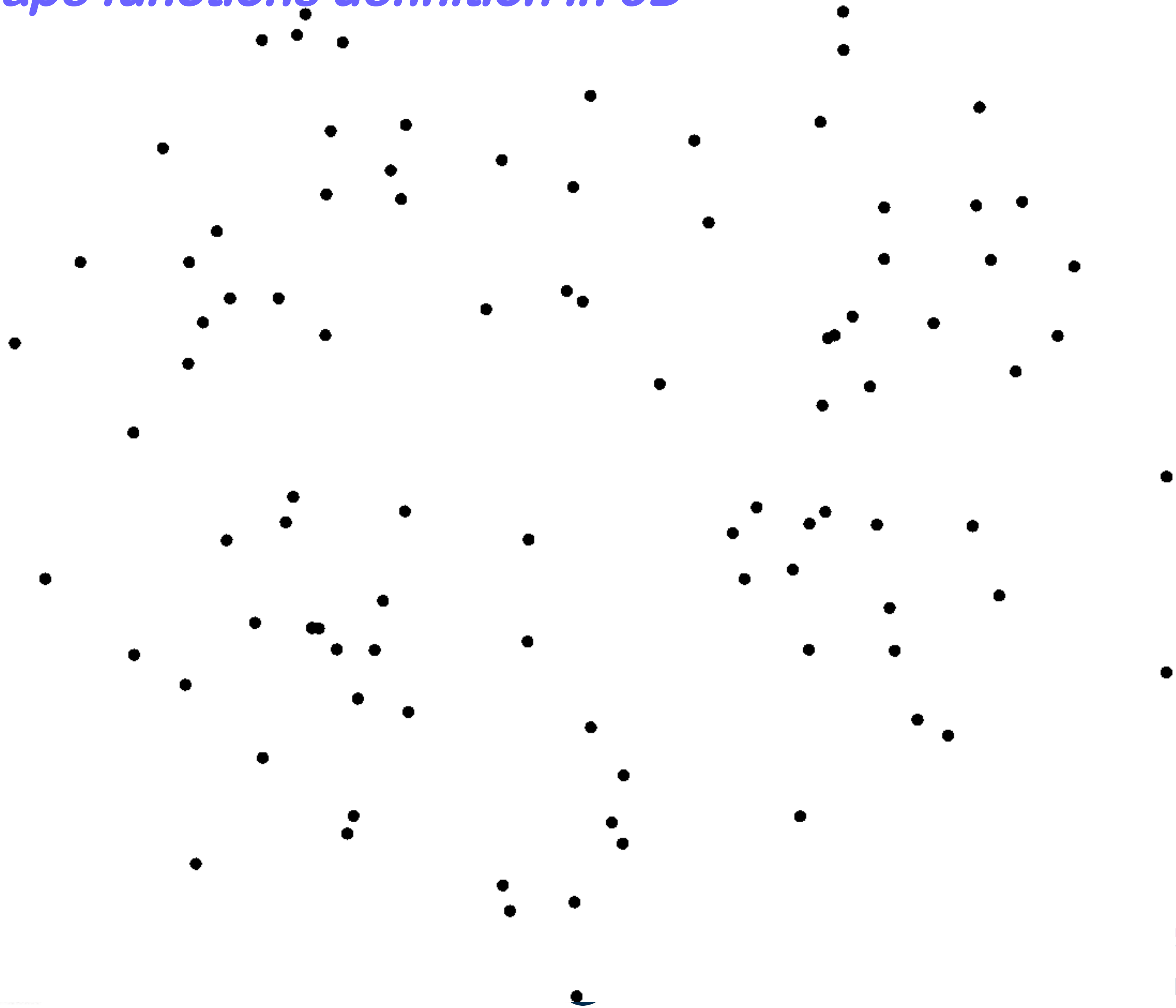
- Linear consistency :

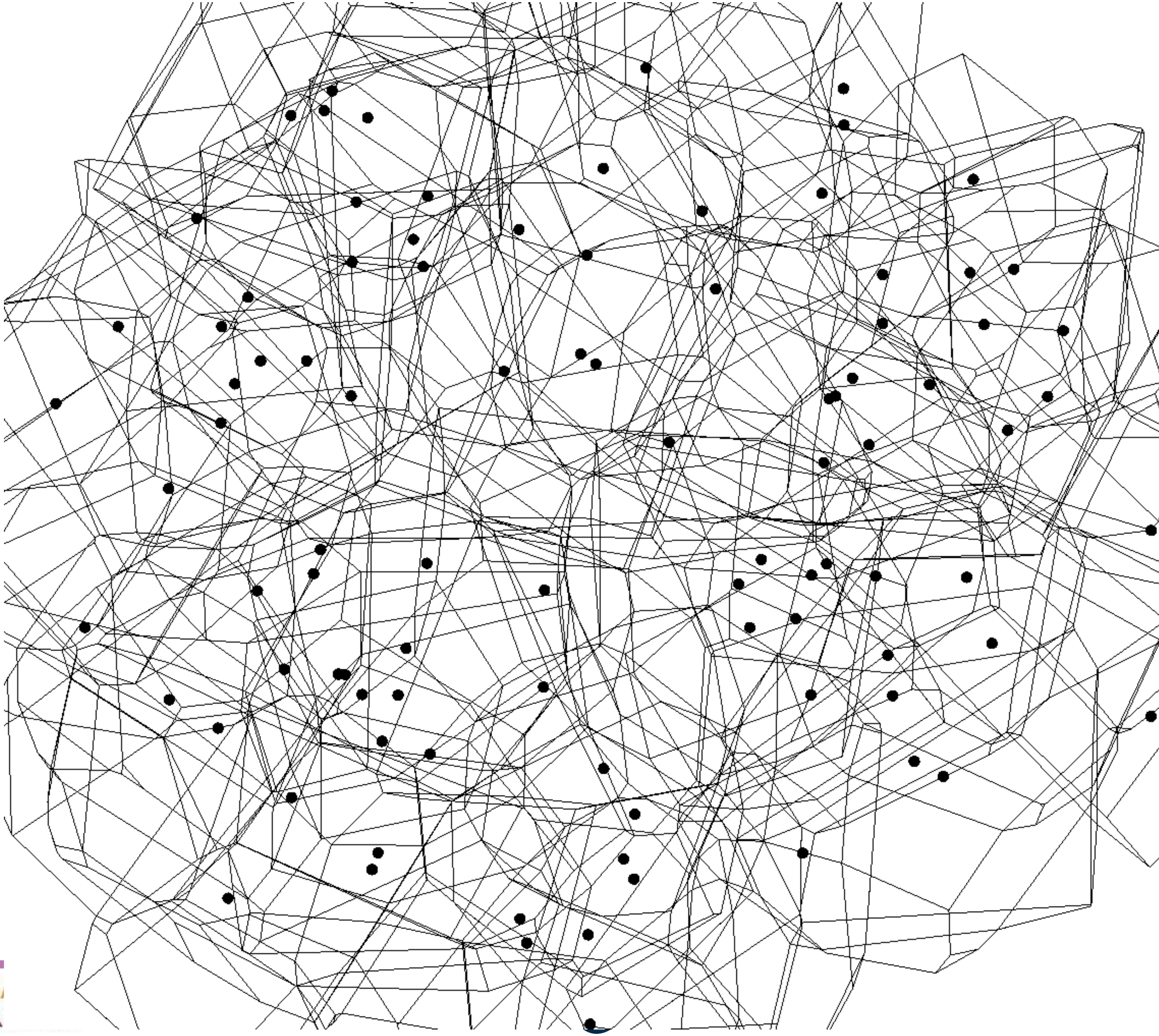
$$\mathbf{x} = \sum_{i=1}^{n} \phi_i(\mathbf{x})\mathbf{x}_i$$

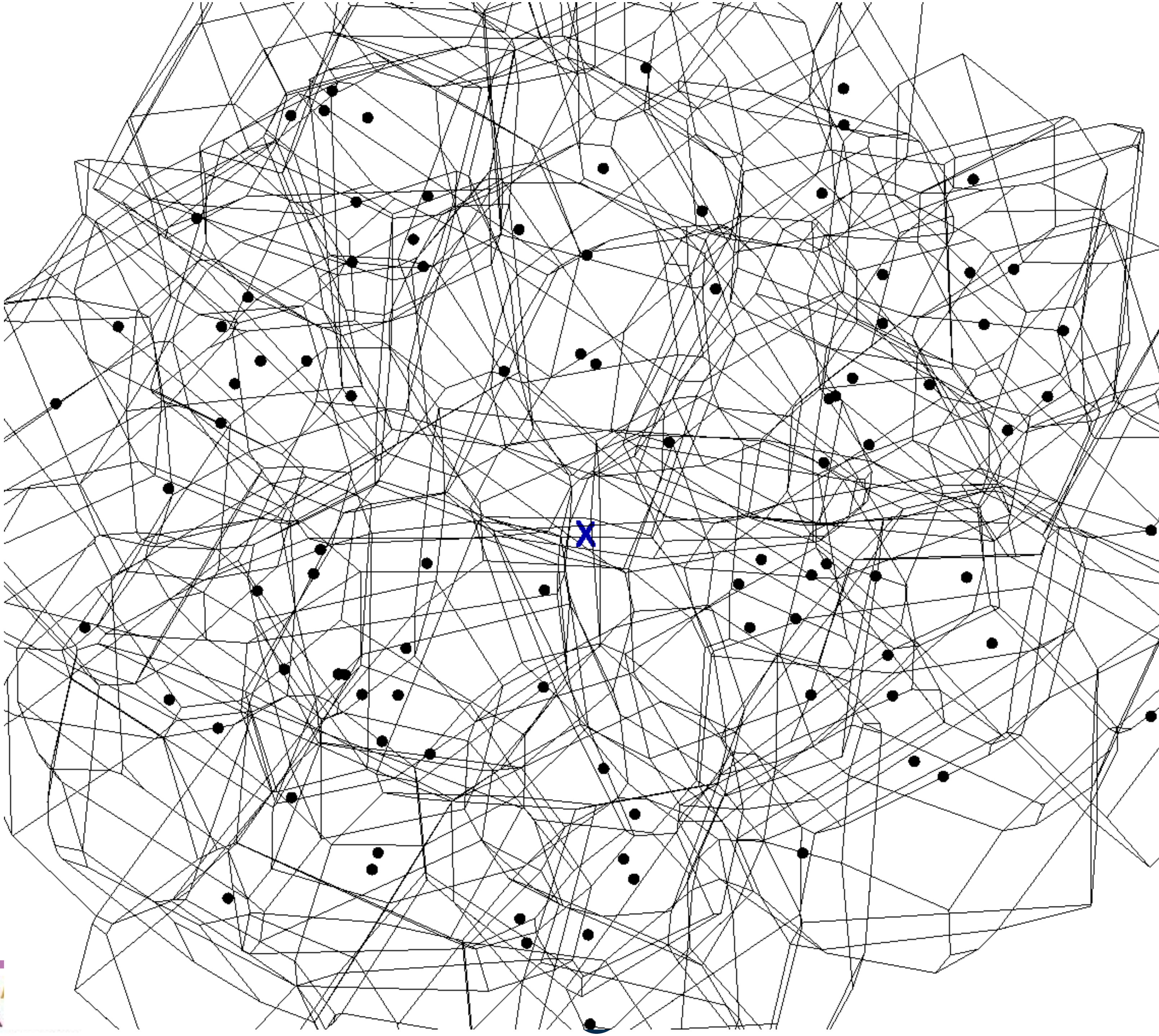
- Shape functions are local in space

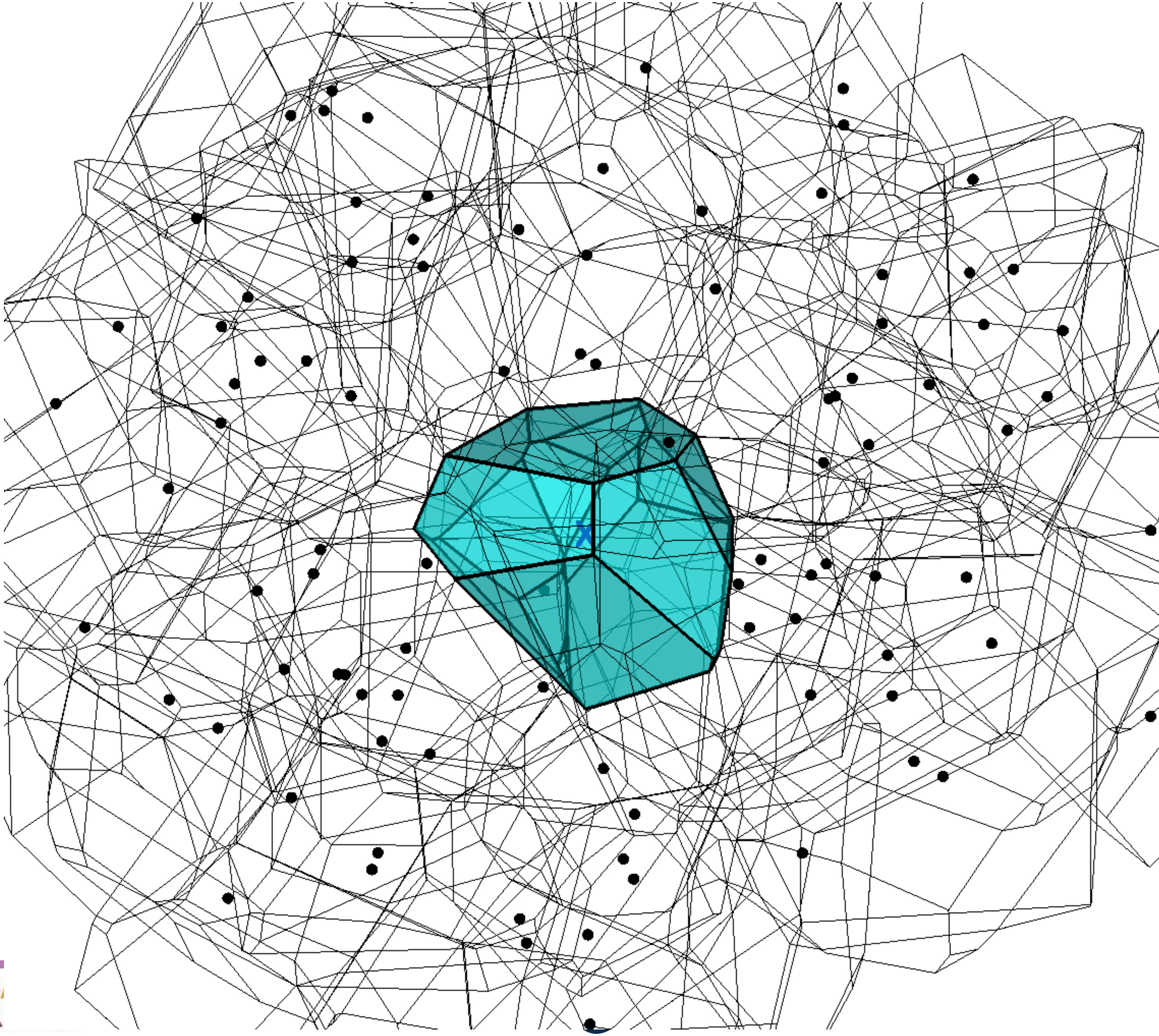
- Shape functions are linear on the domain bounadare

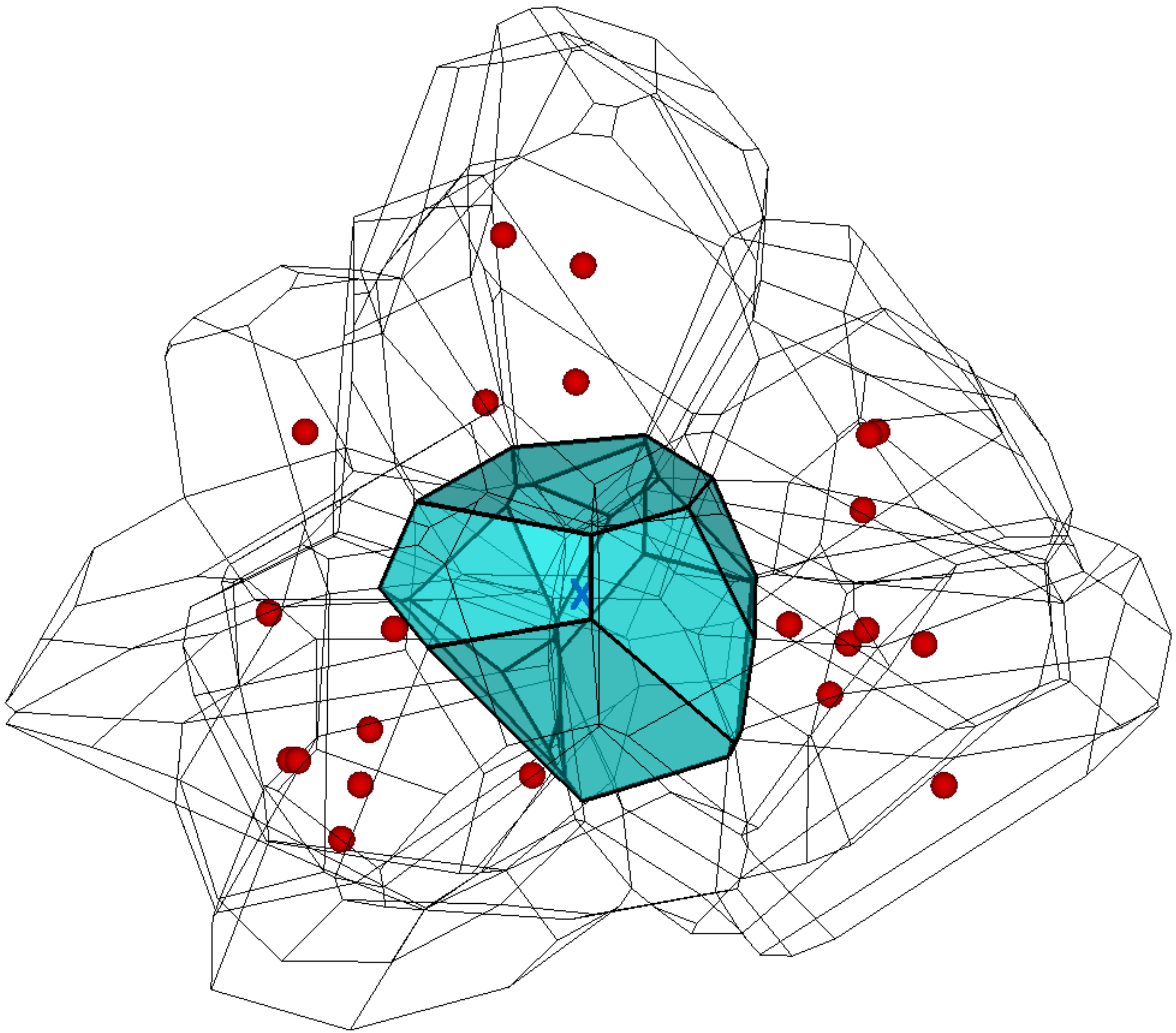
Shape functions definition in 3D

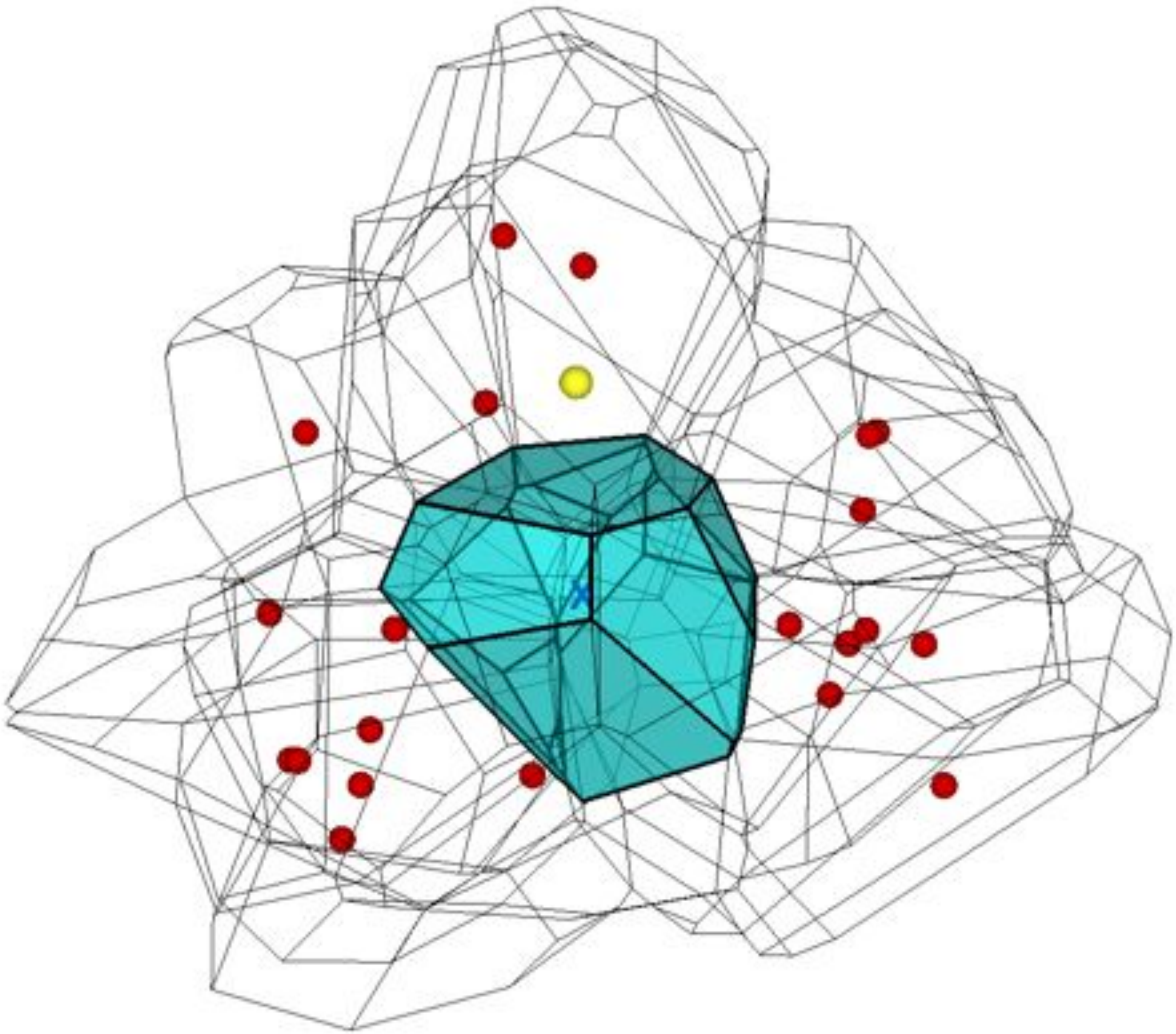


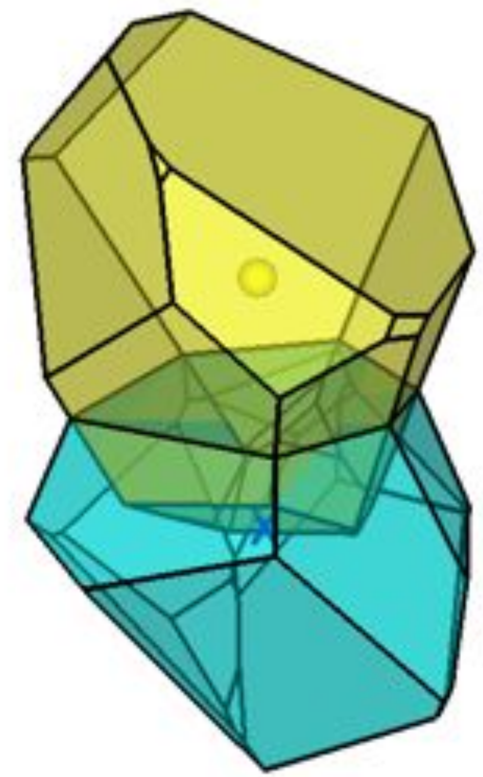


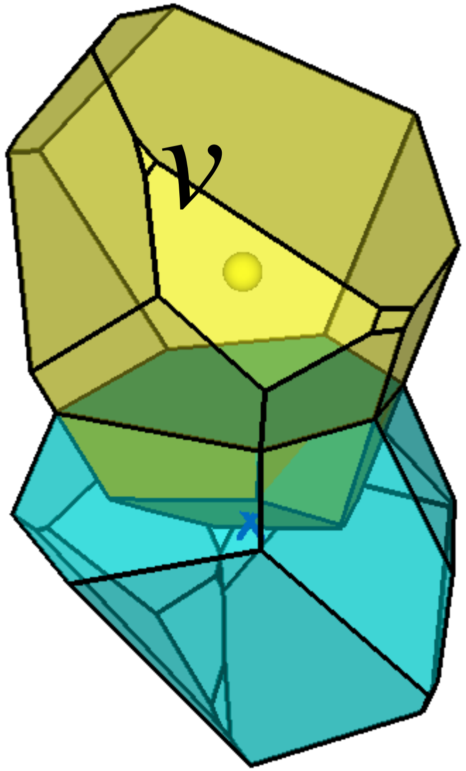

X


x


X

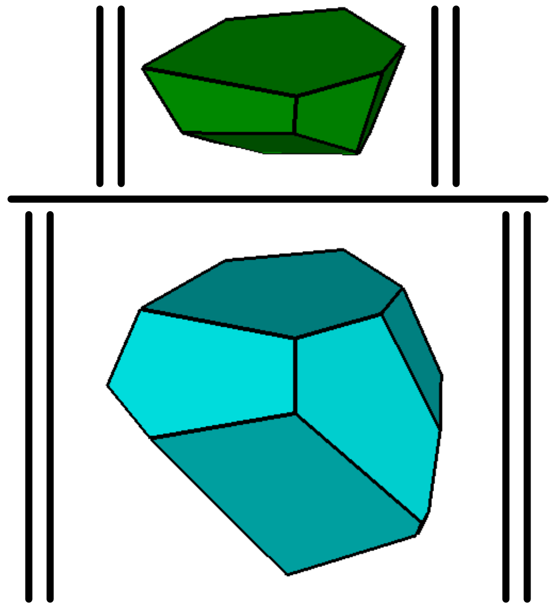






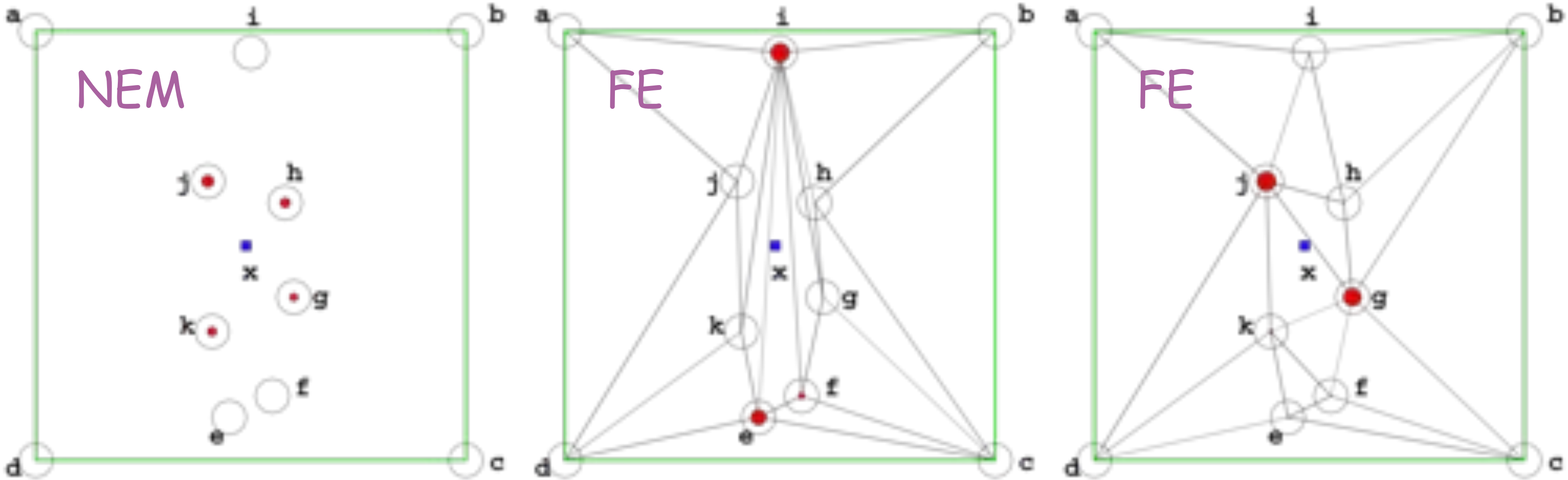
Sibson's interpolant

$$\Phi_v(x) =$$



Fields interpolation : $\mathbf{u}^{\mathbf{h}}(\mathbf{x}) = \sum_{i=1}^{n} \phi_i(\mathbf{x})\mathbf{u}_i$

Shape functions



The quality of the CNEM interpolation :

- depends on the node density
- do not depends on the nodes respective positions

- Initial nodes can be kept during the whole simulation

Data projections are needed only when nodes are added (displacements, temperatures, plastic strains, ..)

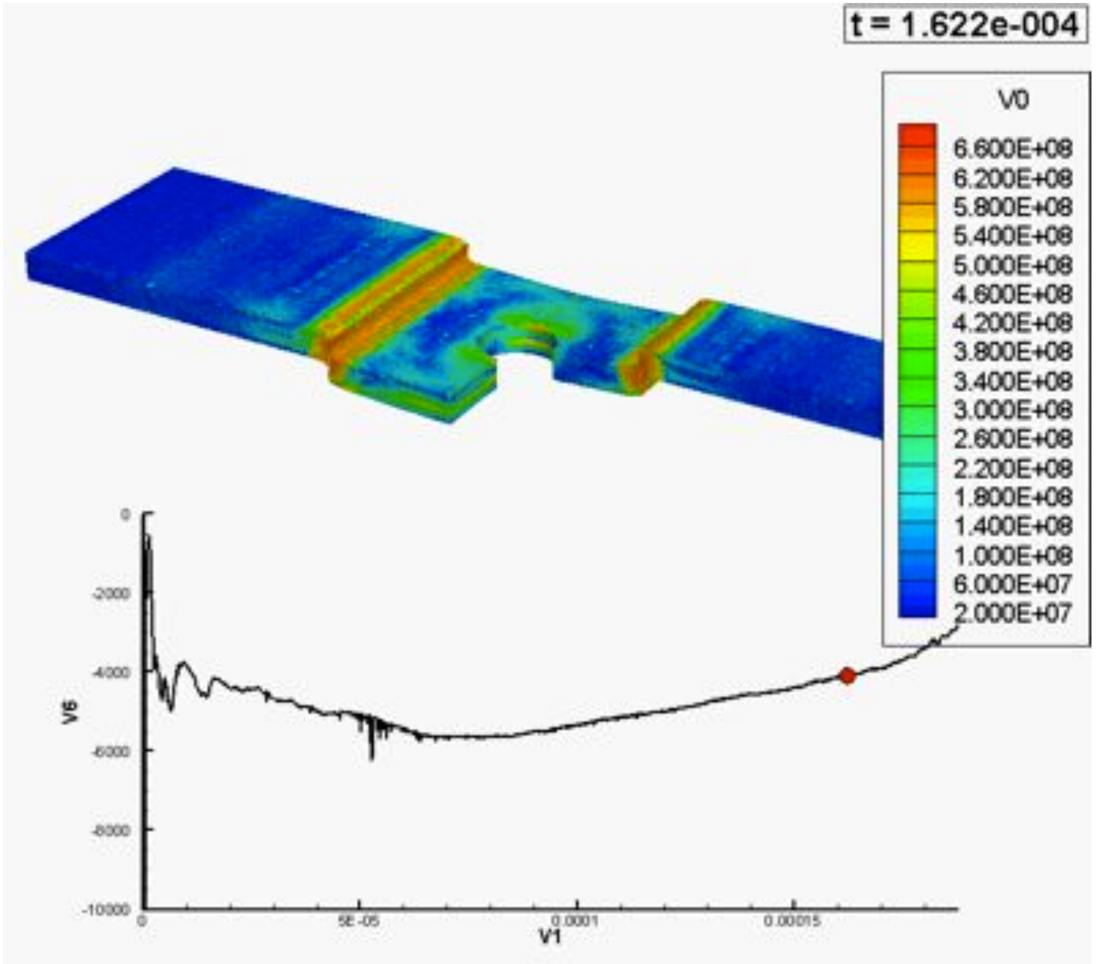
Blanking simulation example

Specificity of the simulation

Integration scheme: Explicit
Update Lagrangian approcah
Constitutive law: Johnson Cook
Thermal conduction inside the part
Die and punch are taken rigid

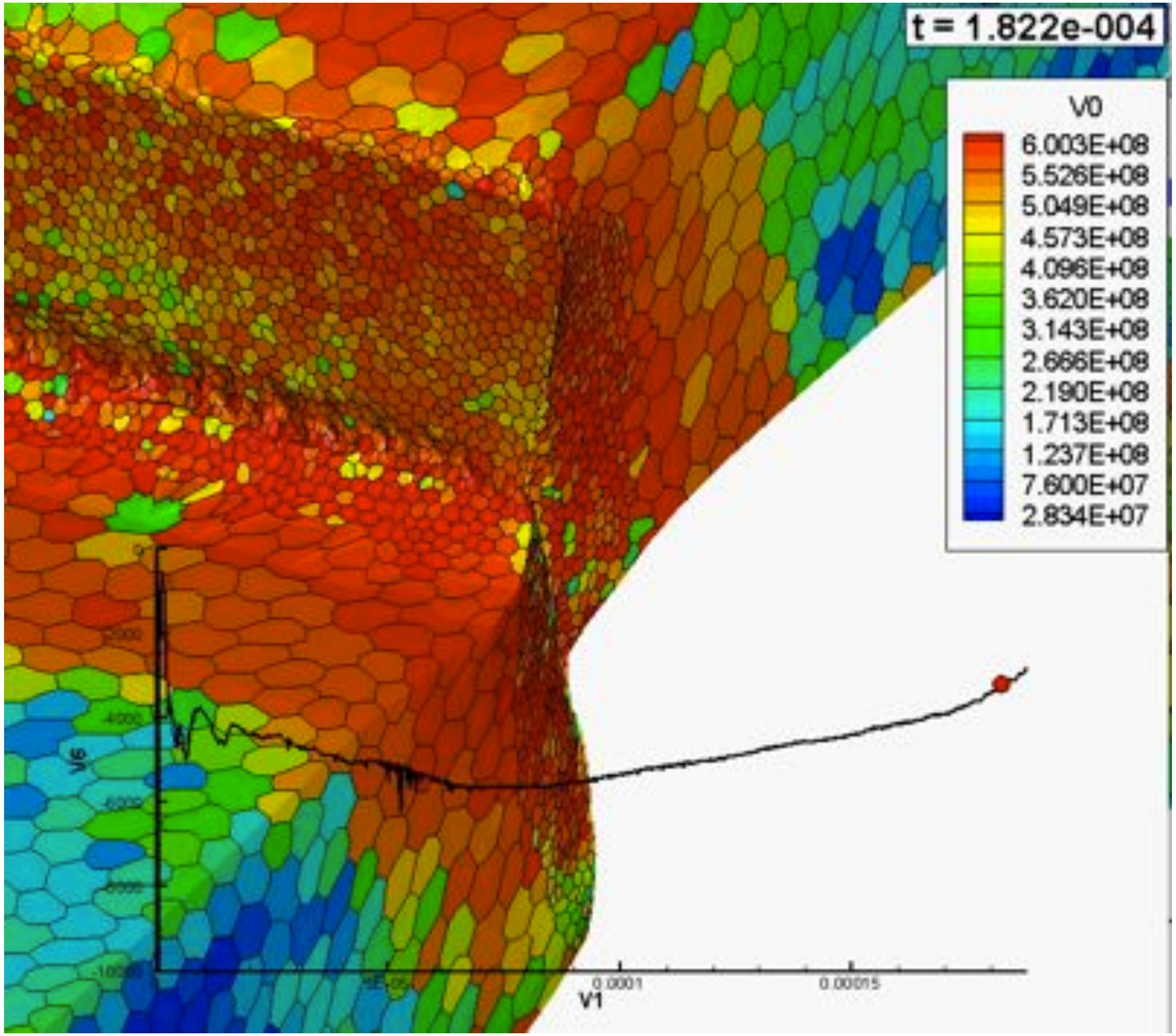
Example:

Mater: TA6V
V = 10 m/s
Lxhxe = 32x17x2mm
j = 0,1mm
r = 0,5mm

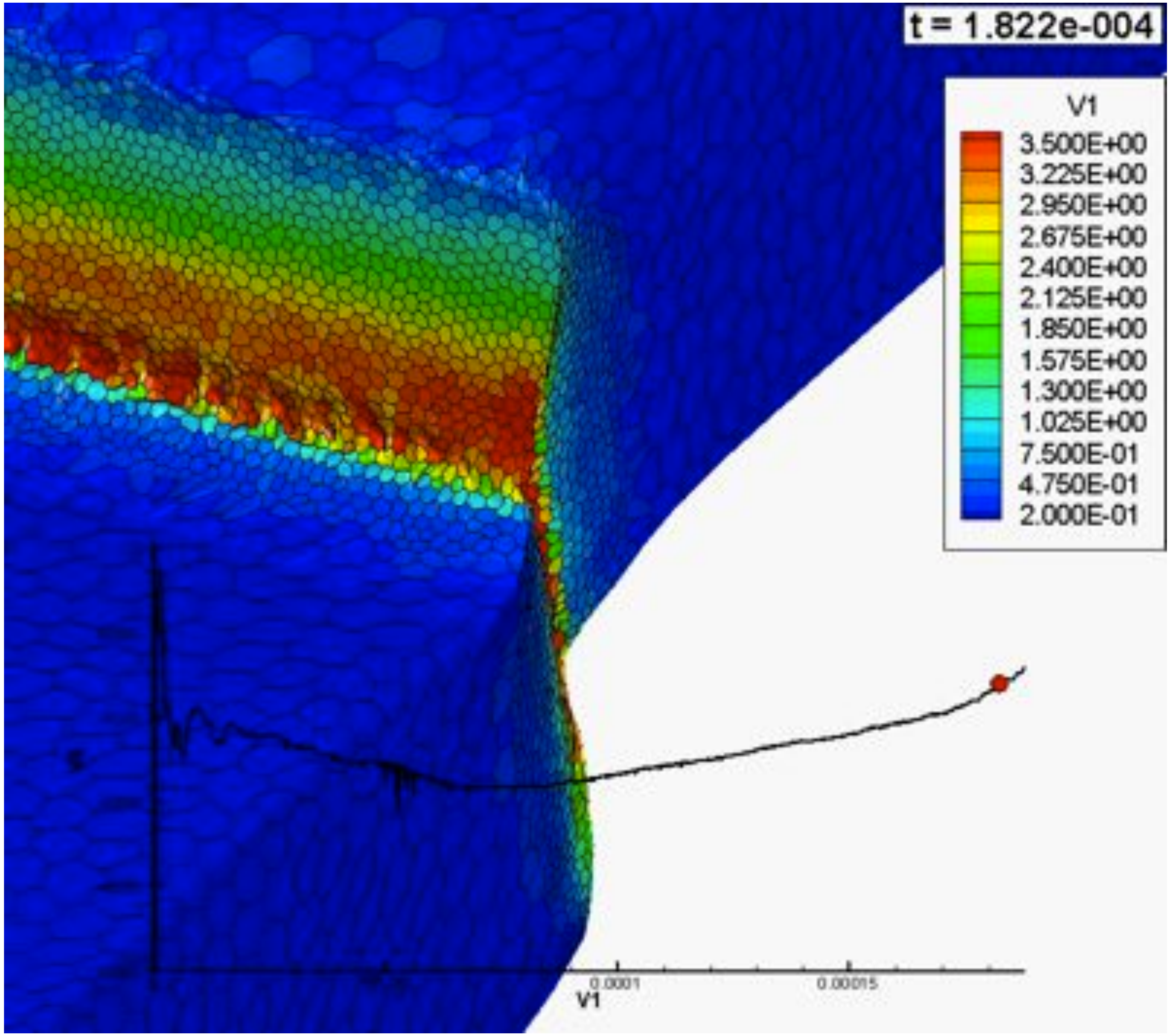


$$\sigma_y(\bar{\varepsilon}^p) = [A + B(\bar{\varepsilon}^p)^n]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}^p}{\dot{\bar{\varepsilon}}_0^p}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]$$

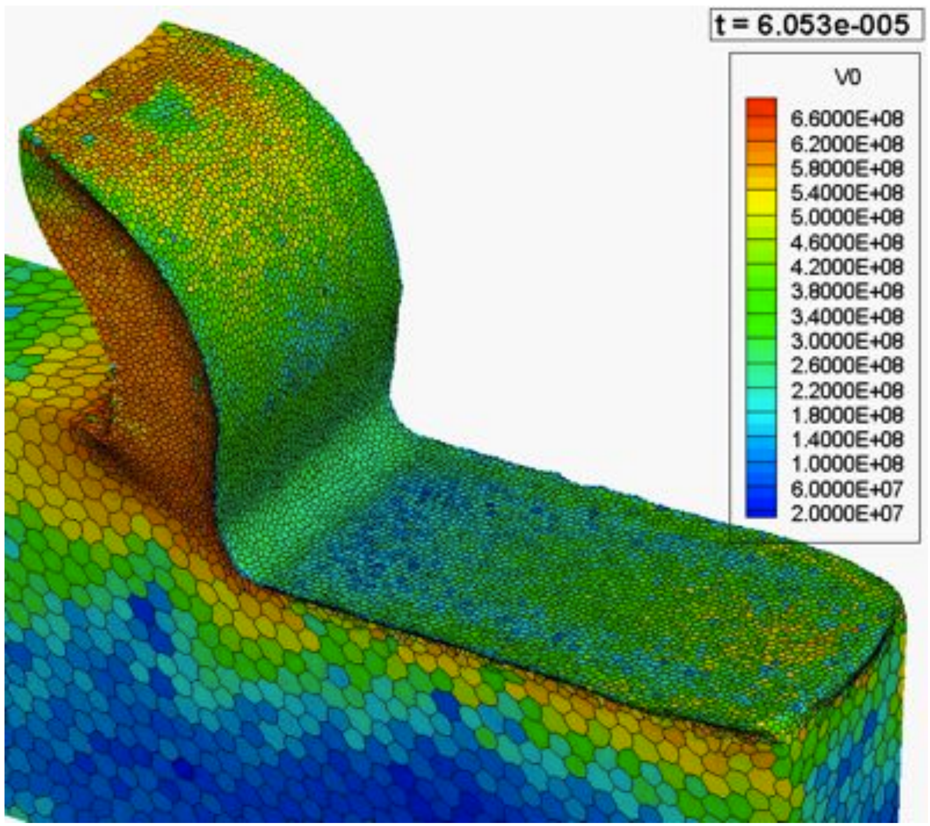
Blanking simulation example



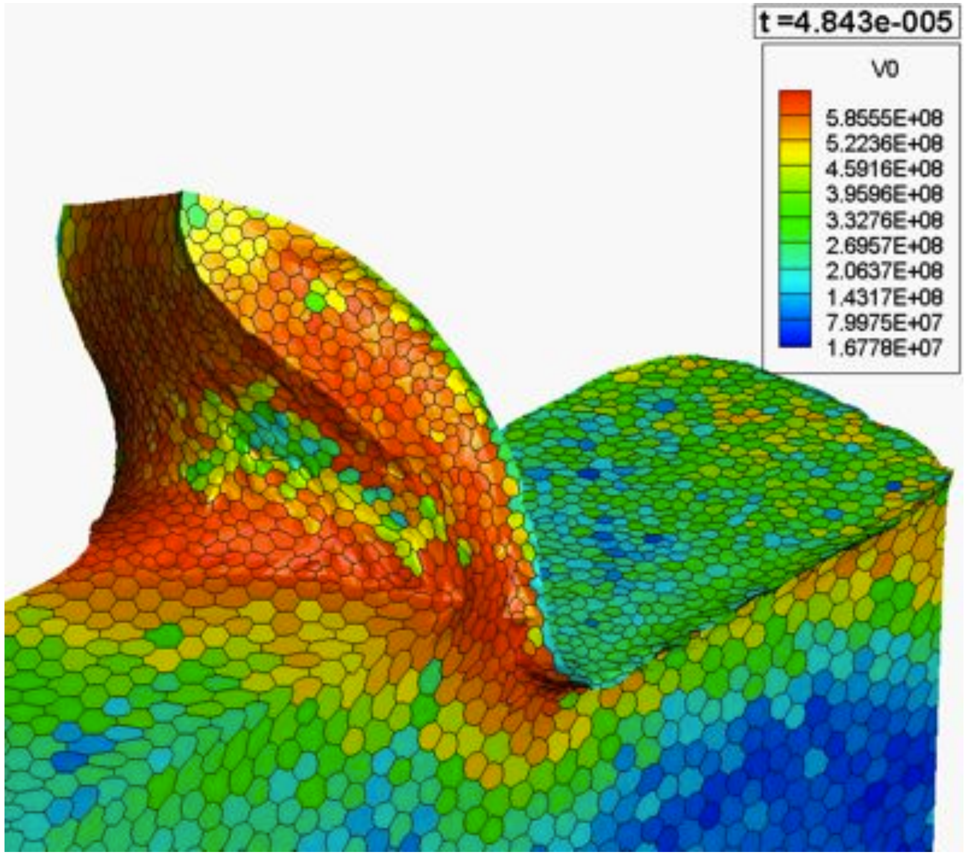
Blanking simulation example



3D Machining simulation example



Orthogonal cutting



Oblique cutting

Conclusion – Macroscopic scale

NEM/CNEM advantages:

- Update Lagrangian : position of the nodes are keeping during the configuration actualisation

  → **no field's projections needed,** except for new nodes
- The position of added nodes can be chose very freely

CNEM disadvantages:

- **Requires a correct description (tessellation)**

  of the domain boundary.

  This description must be actualised too.

In finite transformations :

→ ability of the CNEM to simulate 3d high material distortions

→ the next challenge : handle mater separation and self contact

CNEM is still on work … R