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Influence of the Material Behavior Law and Damage Value on the Results of an Orthogonal Cutting Finite Element Model of Ti6Al4V

MECA

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Introduction

- Modeling of machining processes:
  - Widely used in addition to experiments to provide a better understanding of cutting mechanics
  - Reduces costs by limiting the number of experiments
  - Provides access to hard-to-measure values such as temperature or residual stresses

- Machining = complex process → difficult to be modeled
- Model development involves many parameters influencing the results

- In this presentation:
  - Comparison between modeling and experimental results
  - Influence of material behavior law and damage value on the results will be studied

- Machined material
  - = Ti6Al4V
  - = titanium alloy often used in aeronautical and biomedical applications
- Known to be a difficult-to-machine material producing saw-toothed chips for some cutting conditions

Plan

A. Model presentation

B. Experiments presentation

C. Comparison between numerical and experimental results

D. Improvement of the cutting force

E. Improvement of the morphology

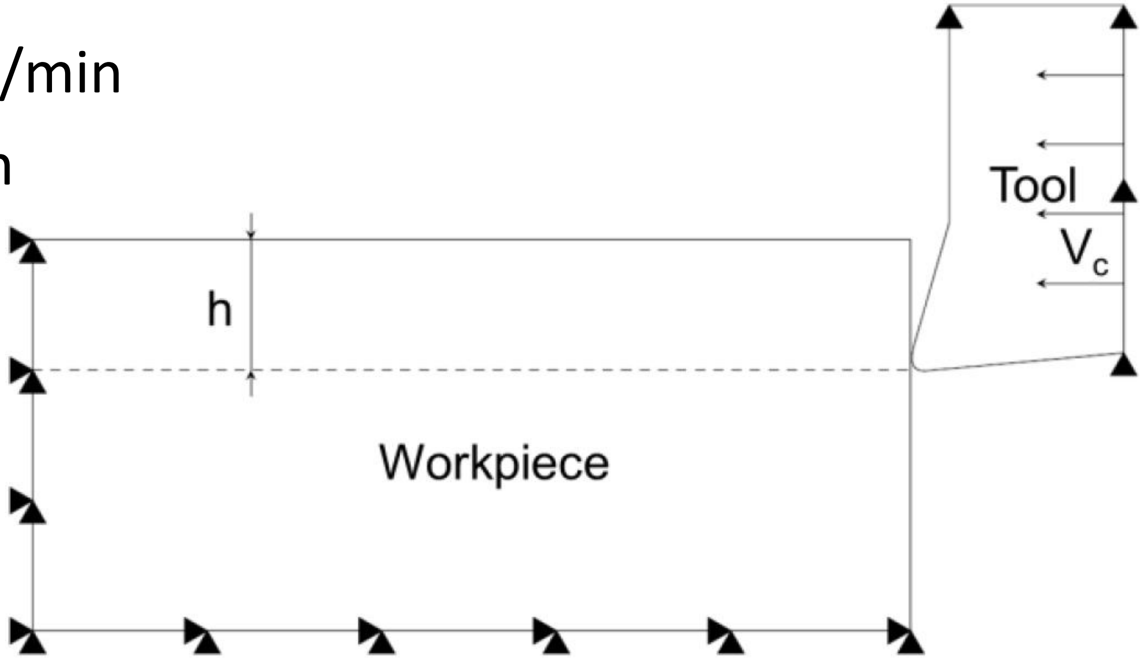
F. Conclusions

A. Model presentation

- Lagrangian Finite Element Method (FEM) model developed
  - to study the depth of cut influence on chip formation in orthogonal cutting [1]
  - with ABAQUS/Explicit
  - in 2D plane strain conditions

- Ducobu, F., Rivière-Lorphèvre, E., Filippi, E., 2011. *A Lagrangian FEM Model to Produce Saw-toothed Macro-chip and to Study the Depth of Cut Influence on its Formation in Orthogonal Cutting of Ti6Al4V*, Advanced Materials Research 223, p. 3.

- Cutting speed (V_c): 30 m/min
- Depth of cut (h): 280 µm
- Initial workpiece shape
  = rectangular box



- Friction at the tool – chip interface implemented using Coulomb's friction (µ = 0.05)
- All the friction energy is converted into heat
- Initial temperature set to 25°C
- Only conduction is considered and all the faces are adiabatic

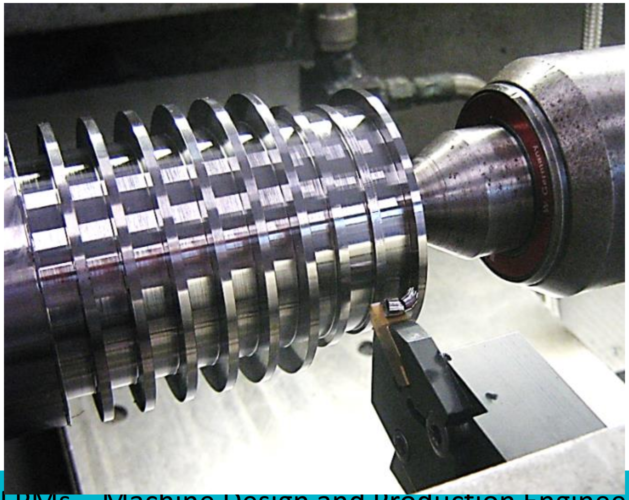
- Workpiece material (Titanium alloy Ti6Al4V):
  - Behavior described by the Hyperbolic TANgent (TANH) law [2]
    = Johnson-Cook law taking account of the strain softening effect
- Tool material: tungsten carbide described by a linear elastic law

- **Lagrangian** formulation → **chip separation criterion** needed
  - Chip formation possible thanks to an "eroding element" method
  - Criterion based on the temperature dependent tensile failure of Ti6Al4V

- Calamaz, M., Coupard, D., Girot, F., 2008. *A new material model for 2D numerical simulation of serrated chip formation when machining titanium alloy Ti-6Al-4V*, International Journal of Machine Tools and Manufacture 48, p. 275.

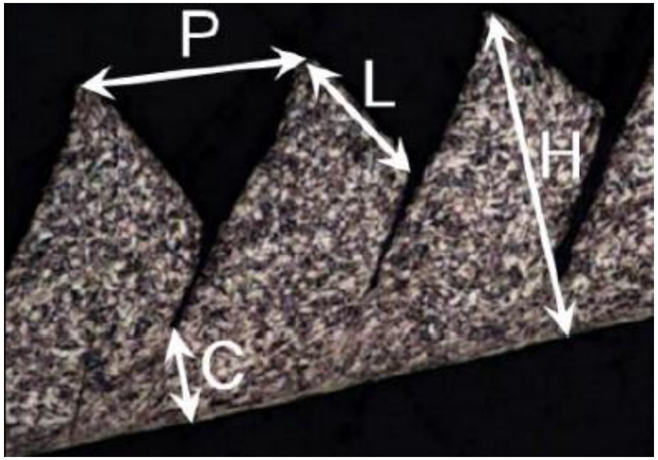
B. Experiments presentation

- Experiments performed on a lathe
- With the same cutting conditions as the numerical model
- In orthogonal cutting conditions
- Ti6Al4V annealed according to AMS 4928
- Forces measured with 9257B Kistler dynamometer



C. Comparison with experimental results

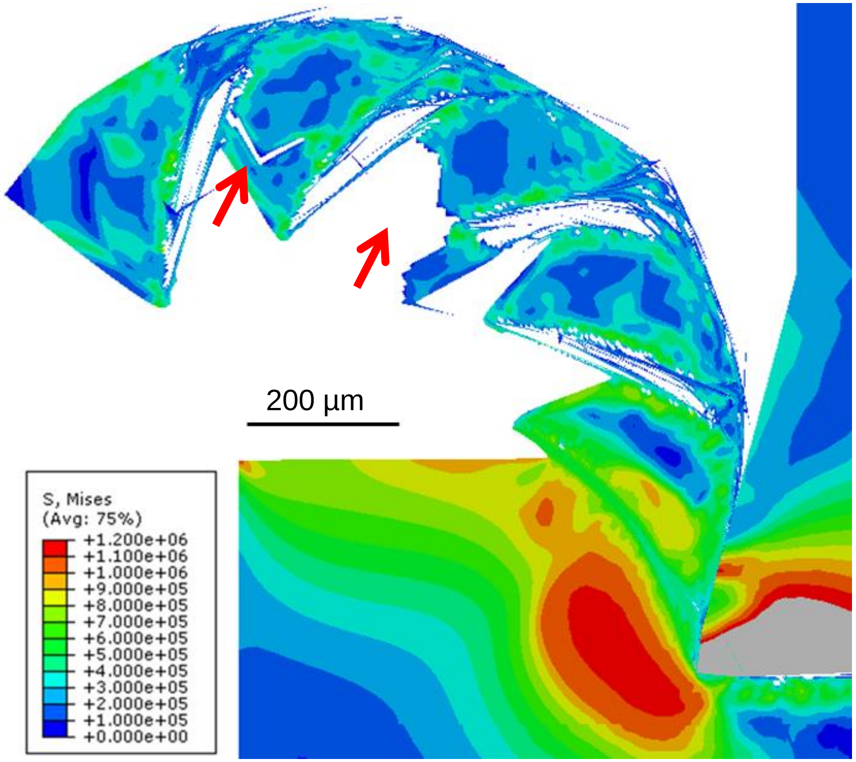
- Experimental chips etched (Kroll's reagent) and polished before observation with an optical microscope
- To characterize a saw-toothed chip, 3 lengths are measured:
  - L: Undeformed tooth length
  - H: Height of the tooth
  - C: Valley



- Pitch (P) usually measured [5] but its value is modified (more than H and C) due to chip unrolling for observation

- Umbrello, D., 2008. *Finite element simulation of conventional and high speed machining of Ti6Al4V alloy*, Journal of Materials Processing Technology 196, p. 79.

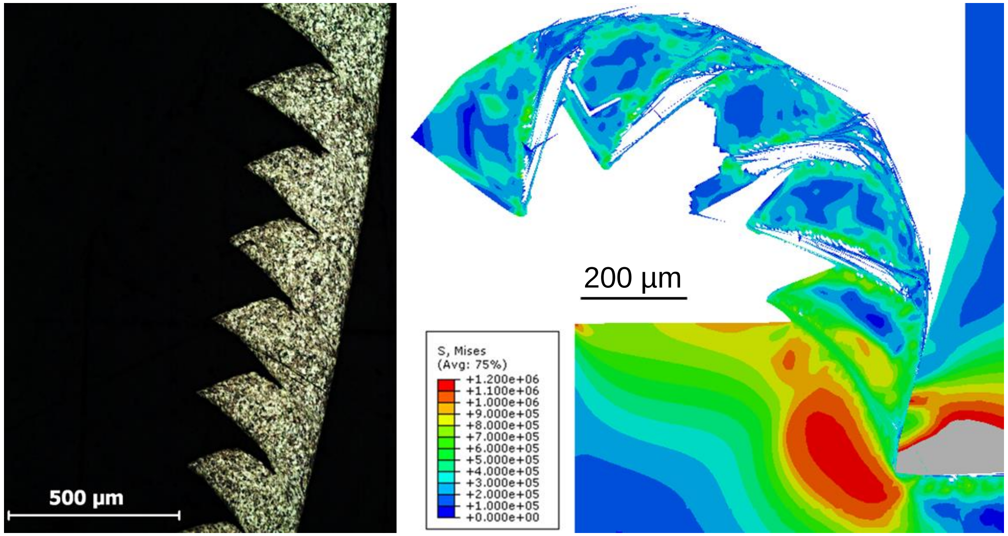
- Experimental and numerical chips are saw-toothed
- Shapes qualitatively close to each other
- 2 differences are highlighted:
  - Numerical teeth are deeper (valley and underformed tooth length smaller)
  - Second and third contain a crack (so long for the 3rd that the tooth is broken)



- Lower numerical valleys and tooth lengths

→ teeth deformation is not sufficient + crack importance is too high

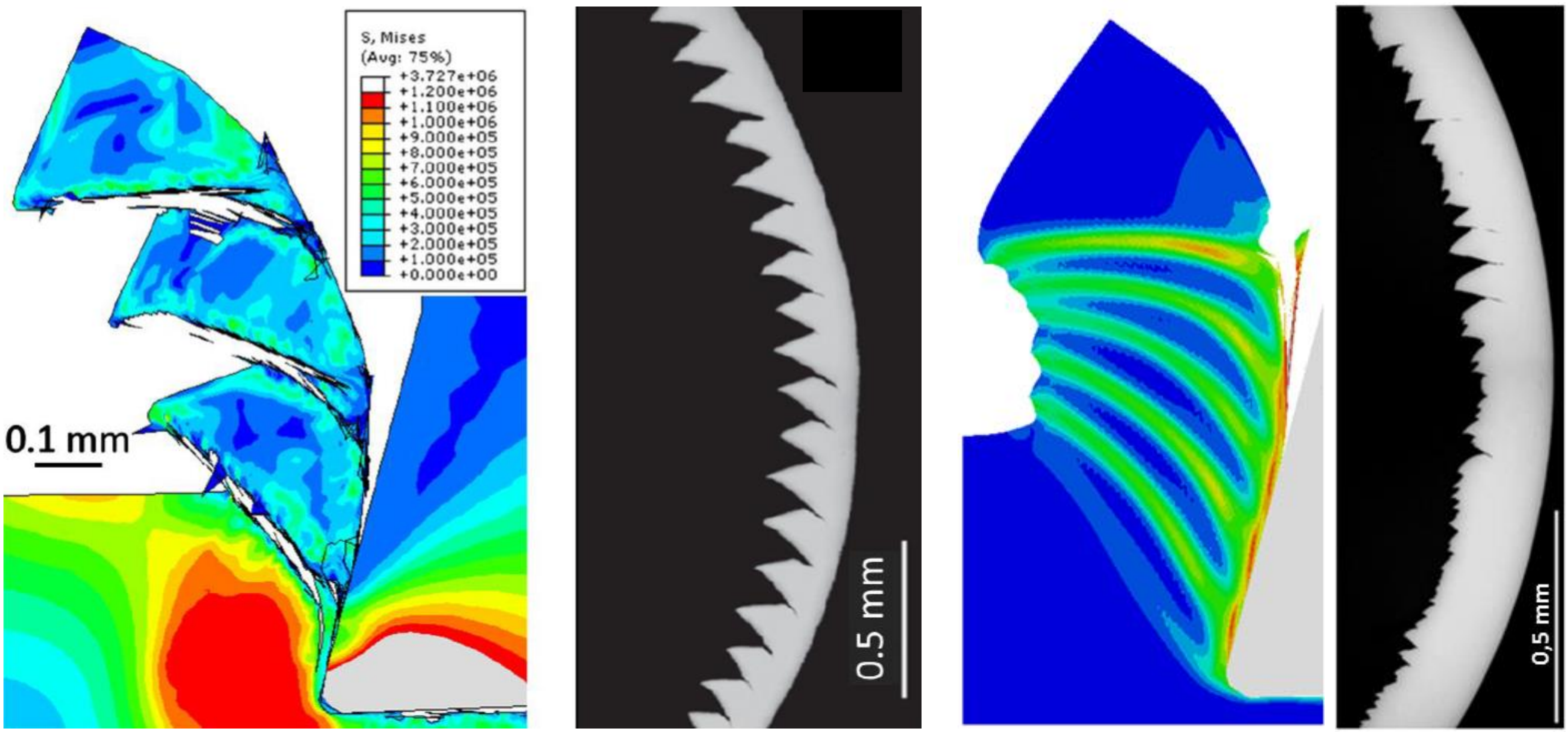
- Numerical chip formation mechanism: strong deformation in PSZ + crack propagation into it from its free surface to the tool



- When analyzing the microstructure of the experimental one: mechanisms very close → the numerical model takes correctly into account the physical phenomena

- It seems however that the crack propagates too easily in the model compared with the experiments

- Morphologies were compared for other cutting conditions [6]
- From saw-toothed to nearly continuous



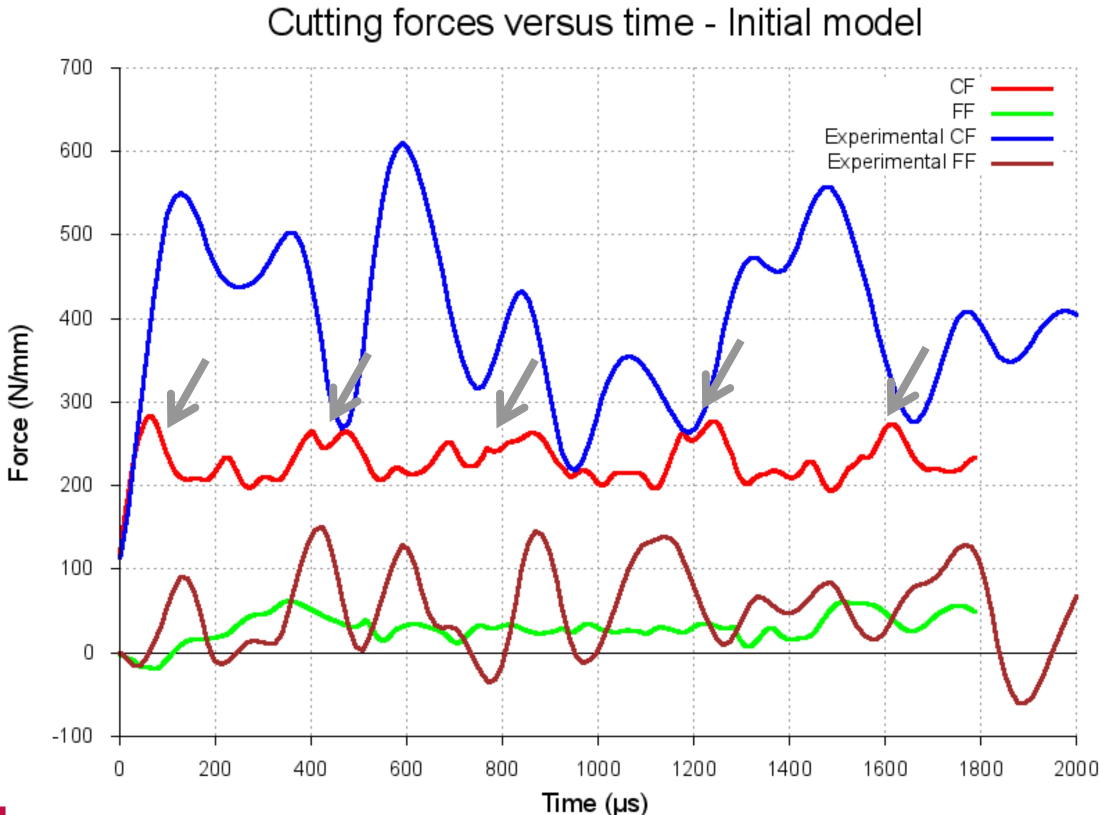
V_c = 75 m/min; h = 280 µm

V_c = 6 m/min; h = 190 µm

- Numerical chips are qualitatively close to experimental ones

- Ducobu, F., 2013. *Contribution to the study of Ti6Al4V chip formation in orthogonal cutting. Numerical and experimental approaches for the comprehension of macroscopic and microscopic cutting mechanisms*, Ph.D. Thesis, UMONS.

- Cyclic evolution of the cutting force = typical of saw-toothed chip formation: a drop in the force = formation of a tooth
- Link between force evolution and teeth formation, 5 maxima = 5 teeth for the numerical chip
- Magnitudes of the variation of the experimental forces are much more important than the numerical ones



- RMS values:
  - The model largely underestimates the cutting force
  - The feed force is very close to the experimental reference

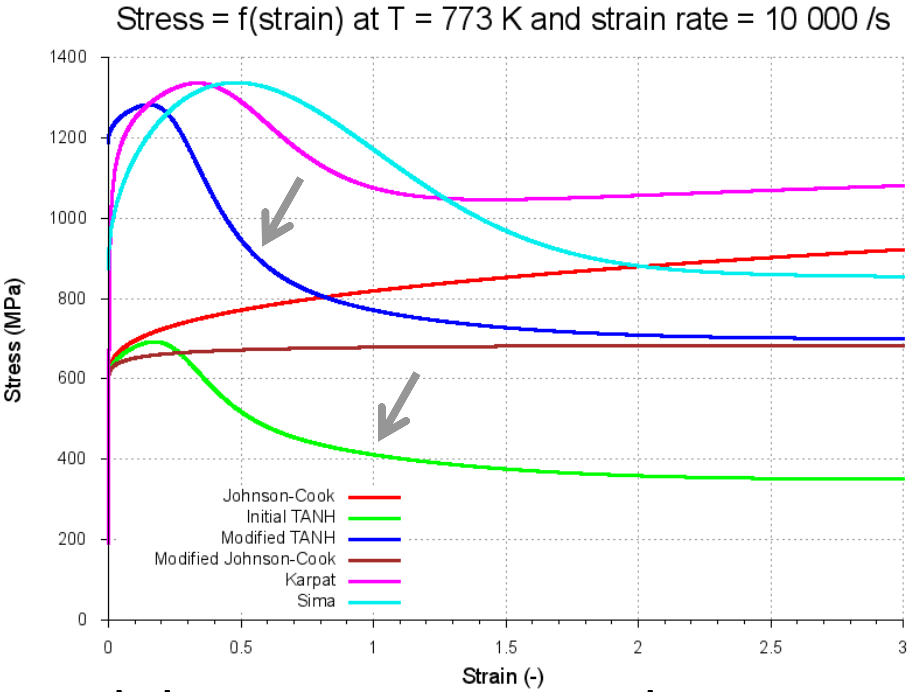
	Experiments	Initial model
CF (N/mm)	387	231
Difference (%)	-	40
FF (N/mm)	77	72
Difference (%)	-	7

- We have no information on the Ti6Al4V metallurgical state used for the identification of the TANH law
- Depending on the behavior law adopted the stresses vary greatly, leading to differences in the forces

→ At this point, it is very likely that the TANH parameters do not correspond to our annealed Ti6Al4V

D. Improvement of the cutting force

- First "adaptation" of the TANH parameters → higher cutting force
- Behavior of machined material + strain softening → many laws
- 2 groups: at small strains, stresses are nearly 2 x smaller → could explain the difference between numerical and experimental CF



- Proposition: pull the TANH curve up while maintaining its shape

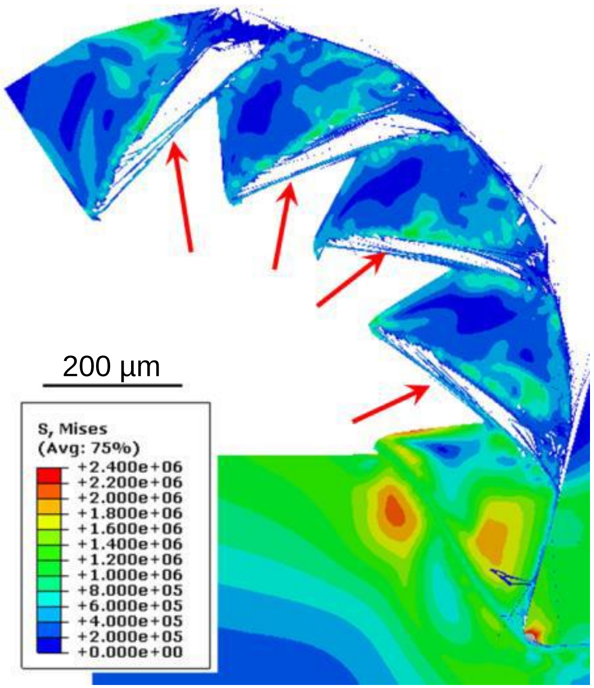
- [2] Calamaz, M., Coupard, D., Girot, F., 2008. *A new material model for 2D numerical simulation of serrated chip formation when machining titanium alloy Ti-6Al-4V*, International Journal of Machine Tools and Manufacture 48, p. 275.
- [7]Calamaz, M., Coupard, D., Nouari, M., Girot, F., 2011. *Numerical analysis of chip formation and shear localisation processes in machining the Ti-6Al-4V titanium alloy,* International Journal of Advanced Manufacturing Technology 52, p. 887.
- [8] Karpat, Y., 2009. "*Finite element modeling of machining titanium alloy Ti-6Al-4V using a modified material model*", 12th CIRP Conference on Modeling of Machining Operations. San Sebastian, Spain, p. 107.
- [9] Sima, M., Özel, T., 2010. *Modified material constitutive models for serrated chip formation simulations and experimental validation in machining of titanium alloy Ti-6Al-4V*, International Journal of Machine Tools and Manufacture 50, p. 943.

Damage modification

- Using the modified TANH law in the model should results in a higher force thanks to larger stresses in the workpiece
- Tensile failure value reached faster → damage value must therefore also be modified
- In consistency with the behavior law, the temperature dependent tensile failure values are also doubled

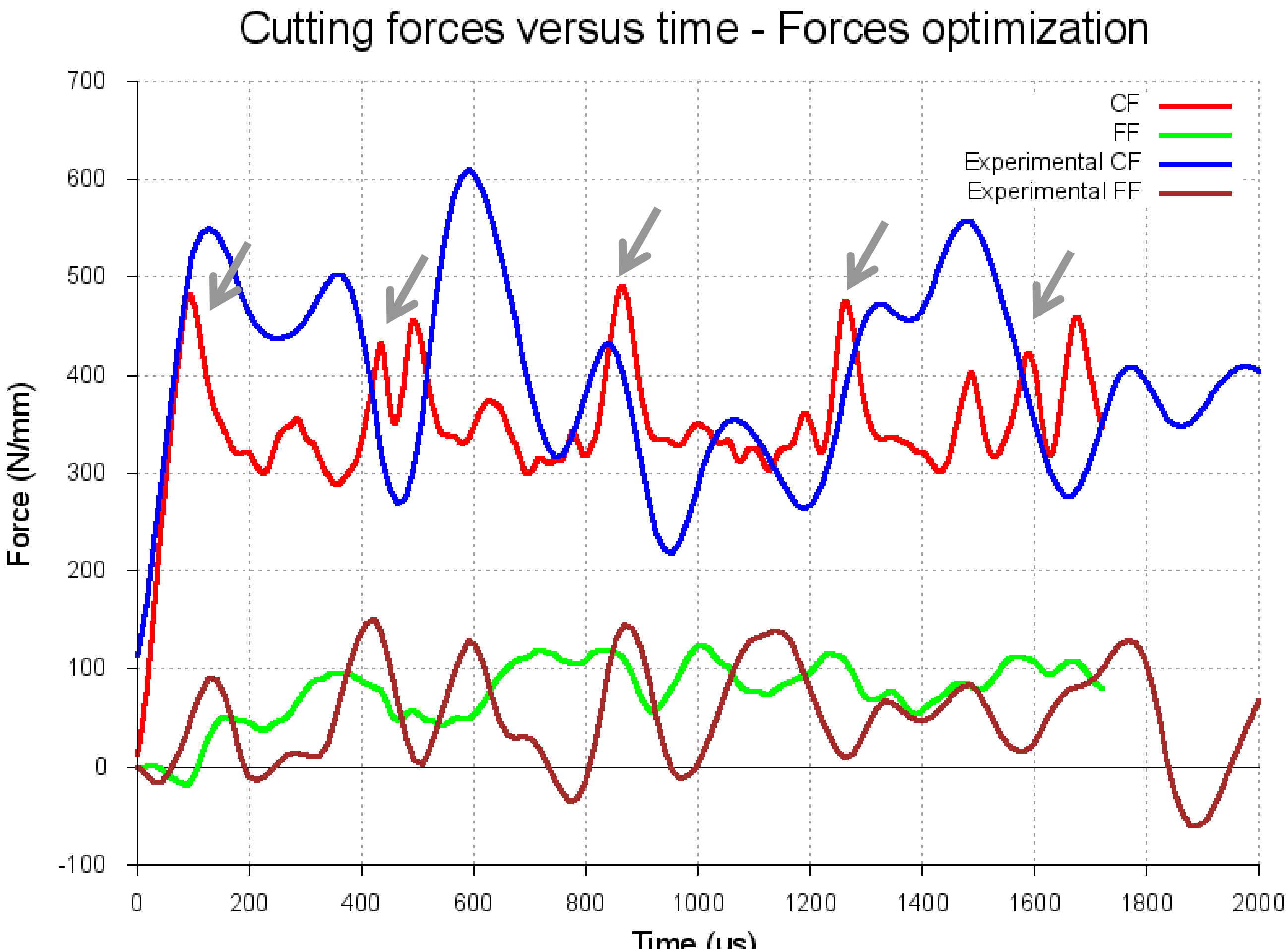
Results

- Chip still saw-toothed, morphology still close to the experiments
- Some teeth are detaching during chip formation due to the conjunction of
  - Crack progressing in the PSZ
  - Second crack starting in the radius area of the tool



- Some elements link to successive teeth → it seems that the chip is still made of one piece
- The drawback observed with the initial TANH law is accentuated to the point of leading to a “discontinuous” chip

- Repercussion of the TANH law modification on CF:
  - higher level, now closer to the experiments
  - magnitude of the variations larger, now closer to the experiments
- As before feed forces are very close



- The rise of the cutting force level → higher RMS value
- The difference between the experimental and numerical CF and FF very small

→ Similar, even smaller, than the best results in literature for Ti6Al4V for other cutting conditions:

  - CF: 5%-10% and FF: 10%-15% [9-11]

	Experiments	Initial model	Modified model
CF (N/mm)	387	231	361
Difference (%)	-	40	7
FF (N/mm)	77	72	86
Difference (%)	-	7	-12

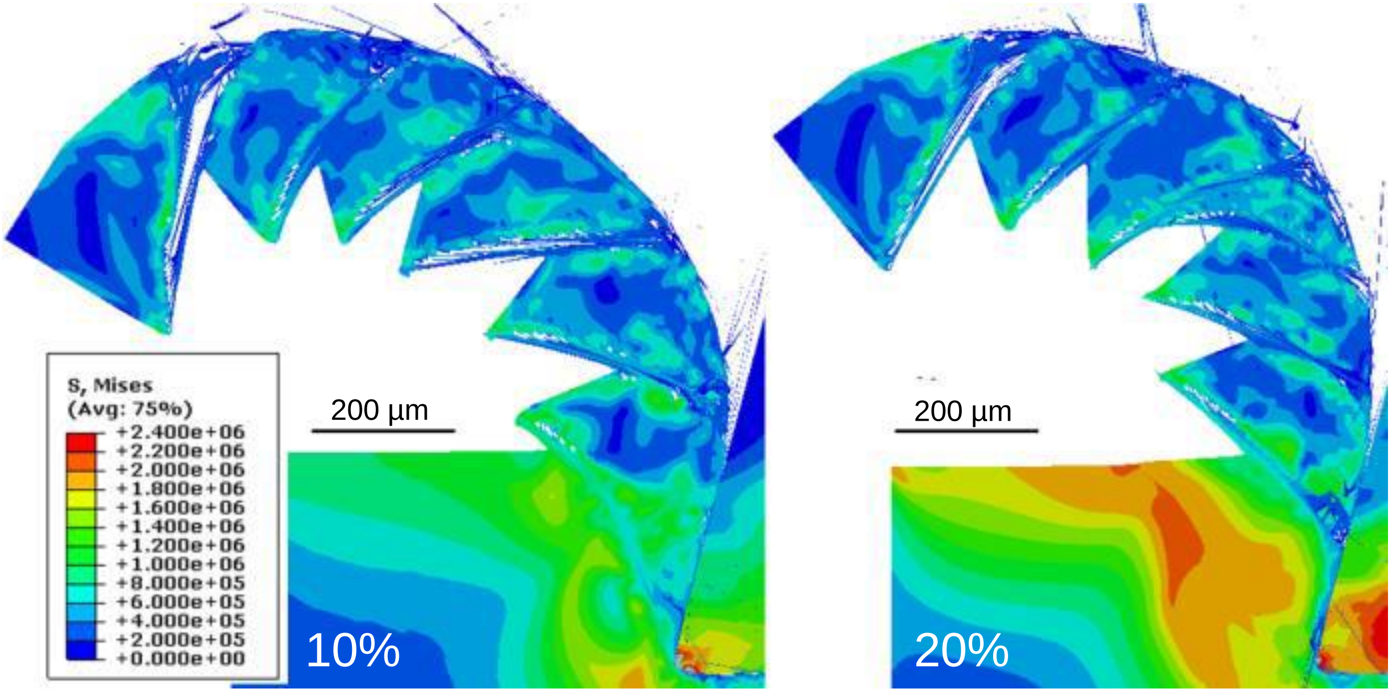
- [[9] Sima, M., Özel, T., 2010. *Modified material constitutive models for serrated chip formation simulations and experimental validation in machining of titanium alloy Ti-6Al-4V*, International Journal of Machine Tools and Manufacture 50, p. 943.
- [10] Karpat, Y, 2011. *Temperature dependent flow softening of titanium alloy Ti6Al4V: An investigation using finite element simulation of machining*, Journal of Materials Processing Technology 211, p. 737.
- [11] Zhang, Y.C., Mabrouki, T., Nelias, D., Gong, Y.D., 2011. *Chip formation in orthogonal cutting considering interface limiting shear stress and damage evolution based on fracture energy approach*, Finite Elements in Analysis and Design 47, p. 850.

E. Improvement of the morphology

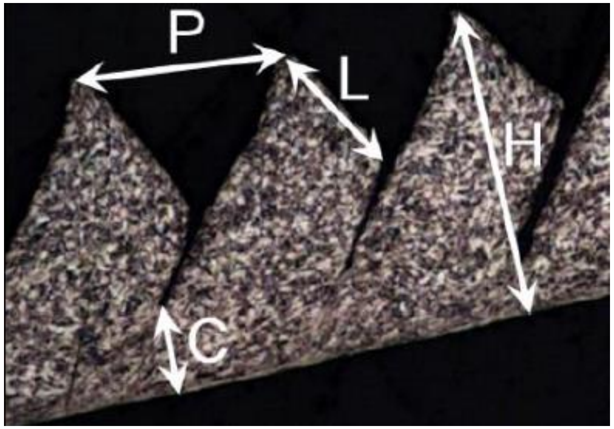
- Only the morphology now needs to be improved to get closer to the experimental one
- 2 previous models: crack propagates too quickly and easily → increase of the damage value
- 2 modifications are considered:
  - Tensile values 10% higher than in the previous model
  - Tensile values 20% higher

- The two chip are saw-toothed and quite similar
- Damage values 20% higher: no crack in the PSZ (except for the first tooth), contrary to the other chip → This damage value might therefore be too high

→ the 10% higher case will be kept



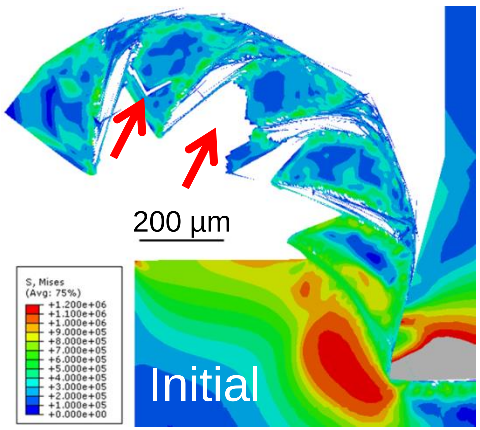
Morphology

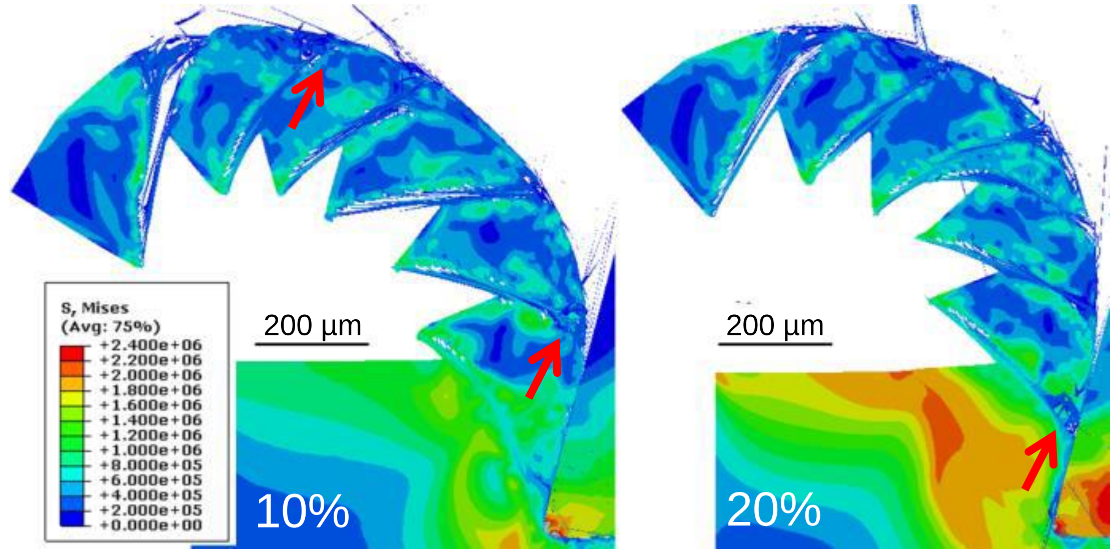


- Measurement of the three lengths
- The length (L) and the height (H) of the numerical teeth still lower than experimental values
  - about 27% for L
  - about 25% for H
- The valley (C) is now larger by round 30% = a maximum (and an overestimation because micro-cracks are not considered)

Chip formation mechanism

- As for the experiments, the numerical chip formation = deformation + crack propagation





- For some teeth: second crack in the cutting edge radius area
  - Similar to the one observed for the first model with the modified TANH law
  - This drawback is therefore not completely eliminated
  - Rise of the damage value does not solve the problem (or at least in the proportions used here): the fifth tooth of the 20% higher model has also a crack like this
- No cracks in the teeth as in the first model = an improvement

Forces

- The RMS values of the cutting forces can be considered as identical
  → such results are not found in literature

- The feed force is higher than for the previous (and also initial) model

	Experiments	Initial model	Modified model	Final model
CF (N/mm)	387	231	361	378
Difference (%)	-	40	7	2
FF (N/mm)	77	72	86	106
Difference (%)	-	7	-12	-38

F. Conclusions

- Main outline of this paper = partial decoupling between the morphology and the forces, at least within the limits of the variations selected
  - Forces level mainly influenced by the behavior law
  - Damage acts mostly on the chip morphology

→ It is possible to modify one without greatly impacting the other

- Modifications of the TANH law can be justified by the initial difference with other laws found in literature as Kartpat’s or Sima’s
- Concerning damage, physical meaning must be used as no data are available to compare to the modified criterion

Thank you for your attention

- Tool:
  - Rake angle: 15°
  - Clearance angle: 2°
  - Edge radius: 20 µm
- Cutting speed: 30 m/min
- Depth of cut: 280 µm
- Initial workpiece shape
  = rectangular box

- Friction at the tool – chip interface implemented using Coulomb's friction
- All the friction energy is converted into heat
- Initial temperature set to 25°C
- Only conduction is considered and all the faces are adiabatic

- **Lagrangian** formulation → **chip separation criterion** needed
- Chip formation possible thanks to an “eroding element” method
- Criterion based on the temperature dependent tensile failure of Ti6Al4V

- Tensile failure value reached in an element

  → deleted from the visualization

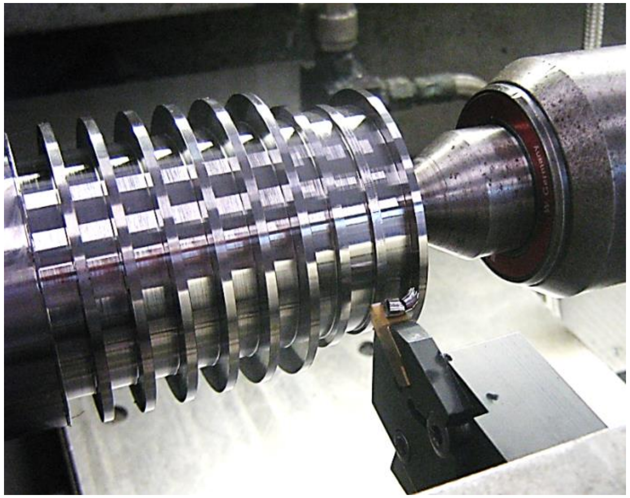
  and all its stress components are put to zero
- Suppression of a finite element

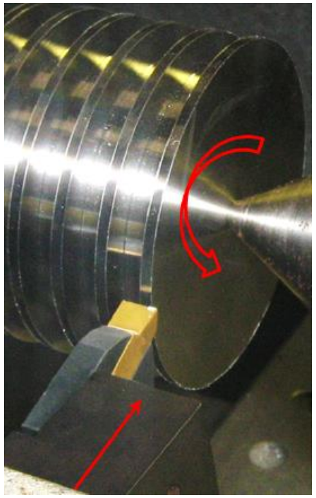
  → introduction of a crack in the workpiece

  → making it possible for the chip to come off

Orthogonal cutting conditions

- Workpiece specimen = shaft comporting flanges in the form of successive slices (diameter 60 mm) of equal thickness (2 mm)
- Tool and tool holder custom made by SECO in order to provide the same characteristics as the numerical model
- Tool width larger than disks width to satisfy plain strain conditions
- Use of a tailstock to avoid workpiece displacements and vibrations
- Forces measured with 9257B Kistler dynamometer





TANH modification

- Proposition: pull the TANH curve up while maintaining its shape
- "Level modification" performed acting on the A parameter
- Numerical force ≈ 40% smaller than the experiments → the value of A is doubled

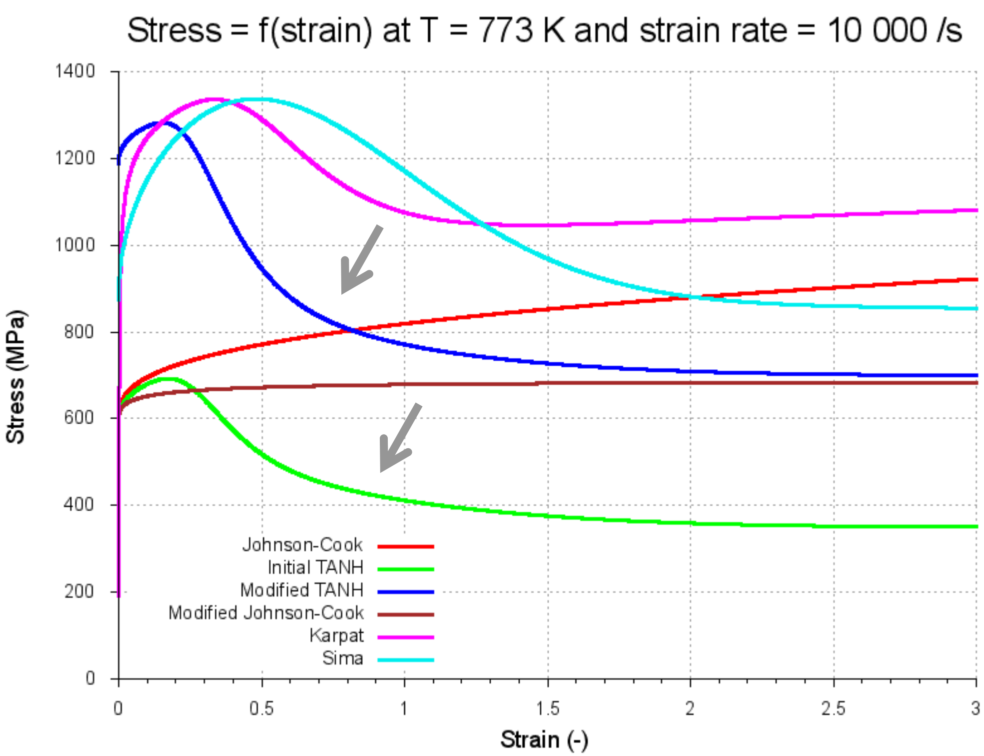
→ Level of modified TANH law closer to Karpat and Sima laws

$$\sigma = \left[A + B\,\varepsilon^n \left(\frac{1}{exp(\varepsilon^a)}\right)\right]\left[1 + C\,ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]$$

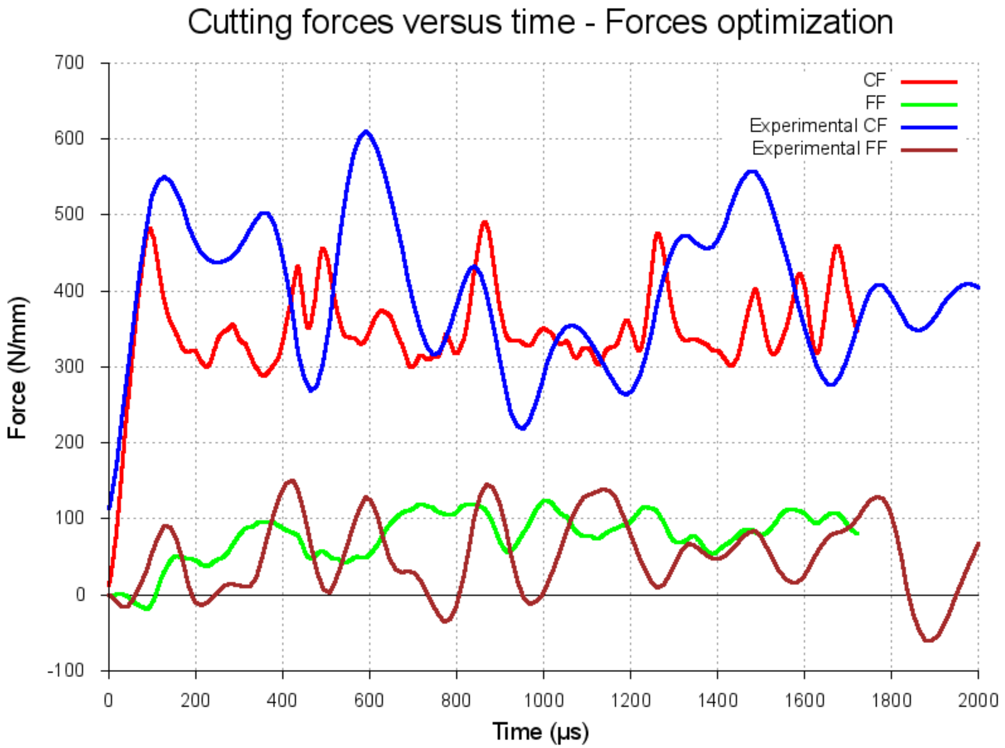
$$\left[1 - \left(\frac{T-T_{room}}{T_{melt}-T_{room}}\right)^m\right]\left[D + (1-D)tanh\left(\frac{1}{(\varepsilon+S)^c}\right)\right]$$

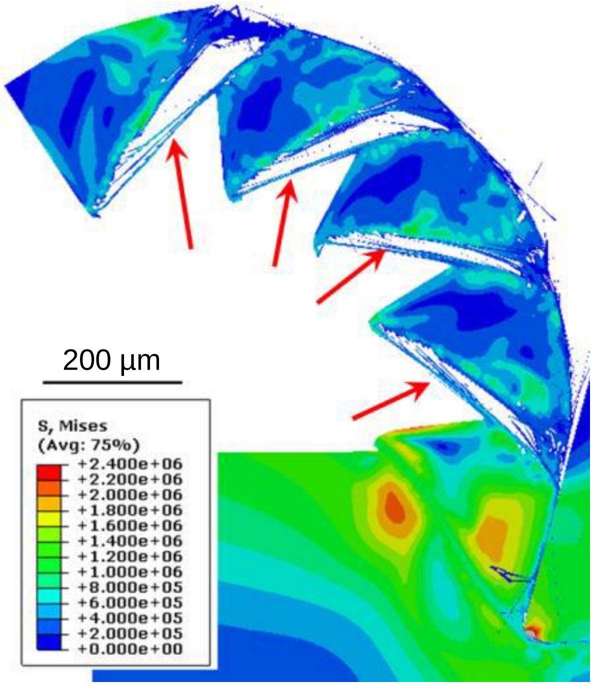
with

$$D = 1 - \left(\frac{T}{T_{melt}}\right)^d \text{ and } S = \left(\frac{T}{T_{melt}}\right)^b$$



- The only notable difference between the two cutting forces is the width of the peaks, larger for the experimental case
- Due to the removal of the teeth:
  - it leads to a quick drop in the force
  - the tool has to move more to be again in contact with the workpiece and the force rises again

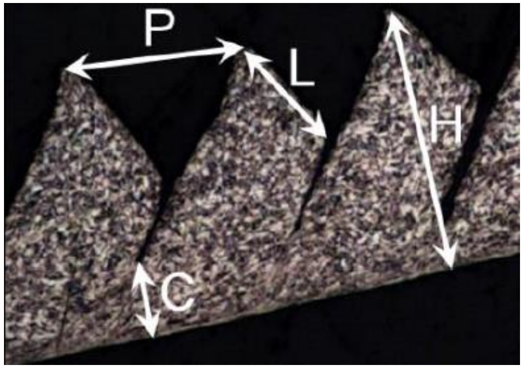




Conclusions: the results are mixed

- ○ Chip morphology deteriorated: problem identified in the initial model → amplified
- ✓ Level of the cutting force closer to the experiments = this increase = the main objective of the TANH law modification → the model fulfills its role on this point
- ▪ Modification the behavior and damage laws in the same proportions → mainly the cutting force is affected

→ The behavior law would therefore mainly acts on the level of the forces without affecting the morphology



Morphology

- Measurement of the three lengths
- Measuring the valley is not easy:
  - micro-cracks in PSZ of the third, fourth and fifth teeth without coming out of the free surface
  - not taken into account, certainly resulting in an overestimation of this value (no micro-cracks were experimentally observed)
- The length (L) and the height (H) of the numerical teeth still lower than experimental values
  - about 27% for L
  - about 25% for H
- The valley (C) is now larger by round 30% = a maximum (and an overestimation because micro-cracks are not considered)

- The final results are very satisfying:
  - ✓ The cutting force is close to the measured one
  - ✓ The morphology is similar to these of the experimental chip
  - ✓ The formation mechanism implies deformation and crack propagation in both cases
  - ✓ The teeth are not too deep anymore and the valley value is closer to the experimental one

  - The parasitical cracks observed in some teeth are not present anymore but others smaller appear in the primary shear zone near the cutting edge radius area

  - ○ The feed force is on the contrary overestimated
  - ○ Micro-cracks are also observed in the primary shear zone for the numerical chip, none were identified during the experiments