CENTRALELYON ENISE

LTDS Tribologie et Dynamique des Systèmes UMR 5513

Simulation des Procédés d'Usinage – Besoins industriels & Verrous

Prof. Joël RECH

Contexte

CONCEPTION

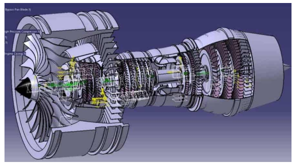
DESSIN

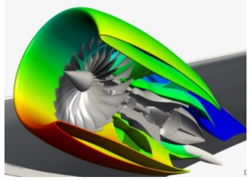
CALCUL

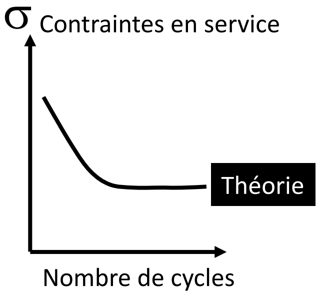
INDUSTRIALISATION (dont USINAGE)

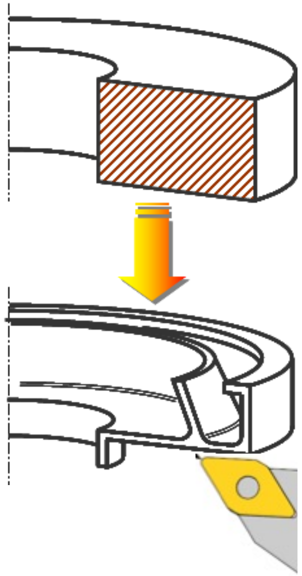
PROTOTYPE / DURABILITE

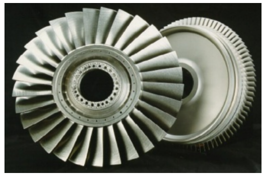
CERTIFICATION

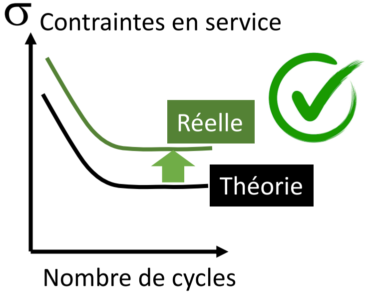






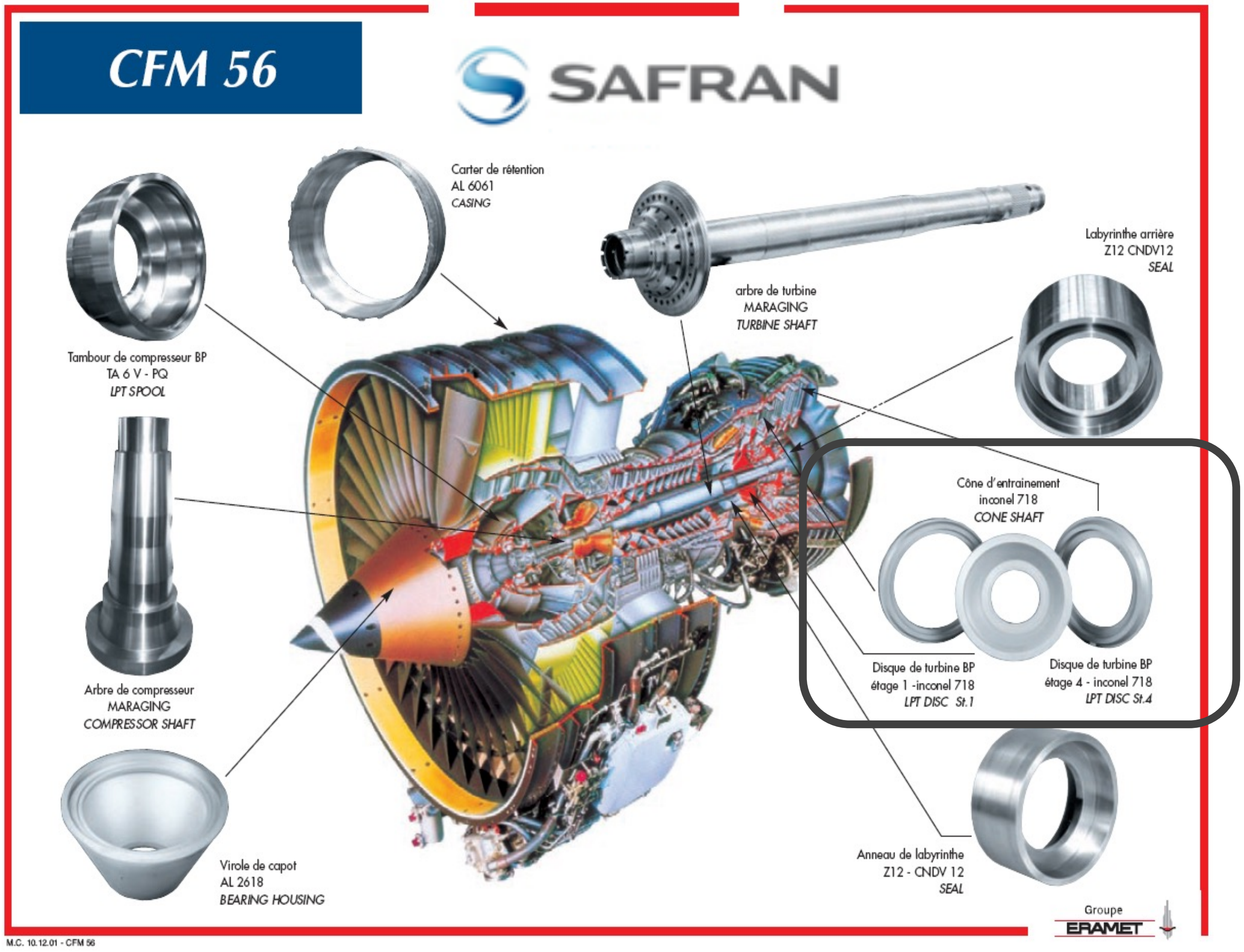






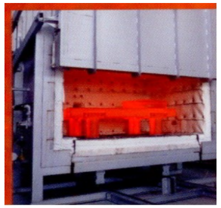
EASA European Aviation Safety Agency

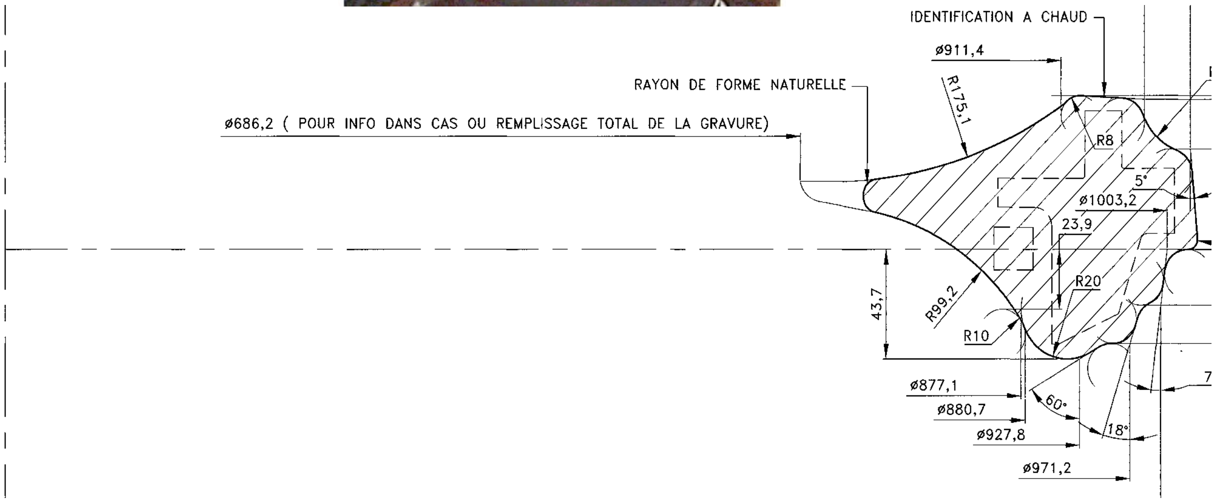
Exemple


CFM 56
SAFRAN
Carter de rétention
AL 6061
CASING
Tambour de compresseur BP
TA 6 V - PQ
LPT SPOOL
arbre de turbine
MARAGING
TURBINE SHAFT
Labyrinthe arrière
Z12 CNDV12
SEAL
Arbre de compresseur
MARAGING
COMPRESSOR SHAFT
Cône d'entraînement
inconel 718
CONE SHAFT
Disque de turbine BP
étage 1 -inconel 718
LPT DISC St.1
Disque de turbine BP
étage 4 - inconel 718
LPT DISC St.4
Virole de capot
AL 2618
BEARING HOUSING
Anneau de labyrinthe
Z12 - CNDV 12
SEAL
Groupe
ERAMET
M.C. 10.12.01 - CFM 56

Gamme de fabrication simplifiée

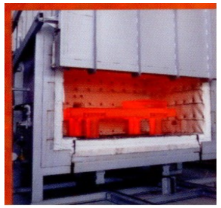
Forgeage → Traitement thermique

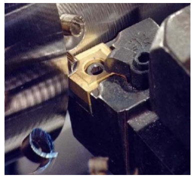


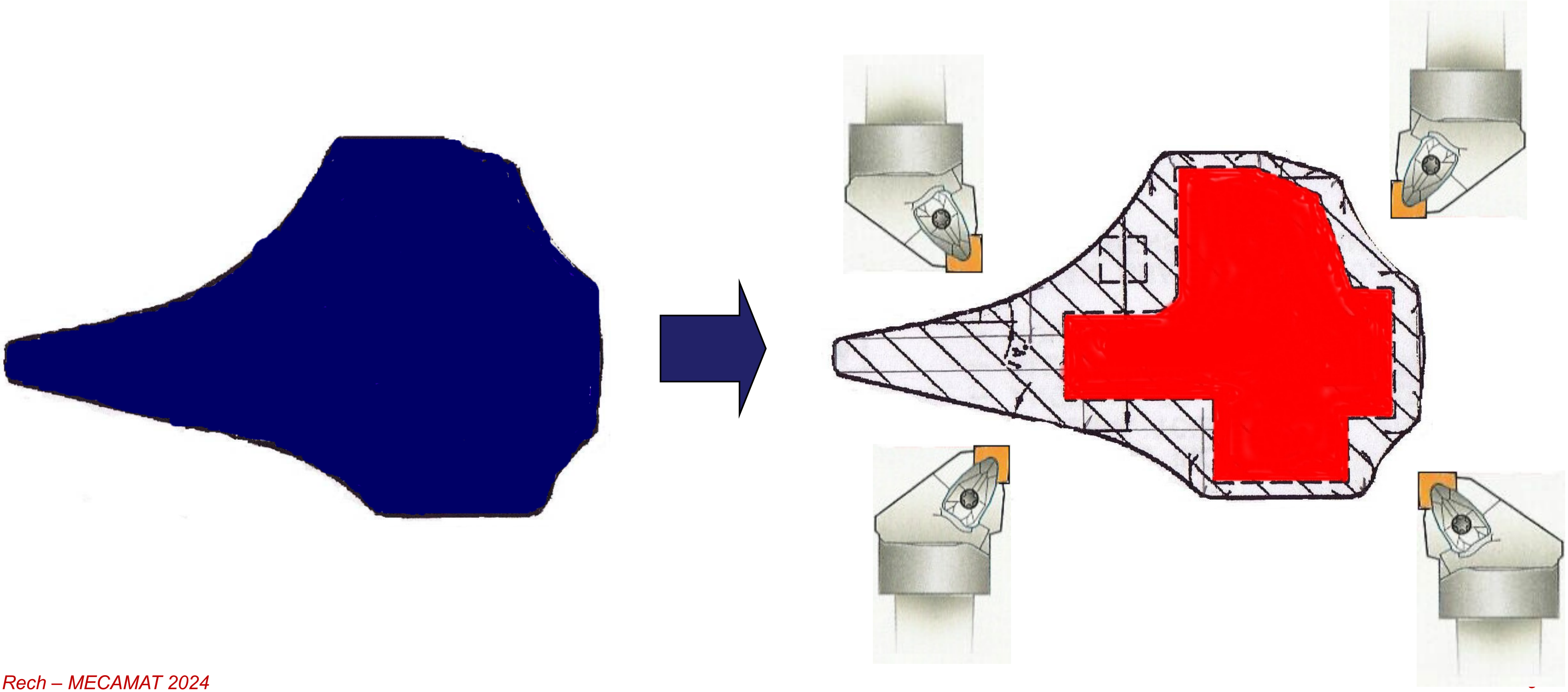


Gamme de fabrication simplifiée

Forgeage → Traitement thermique → Usinage Ebauche

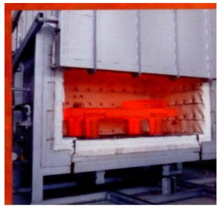


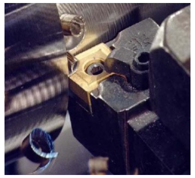


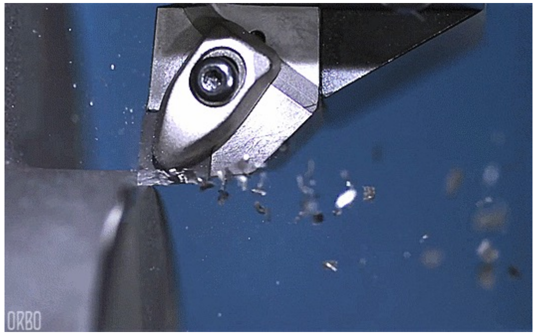


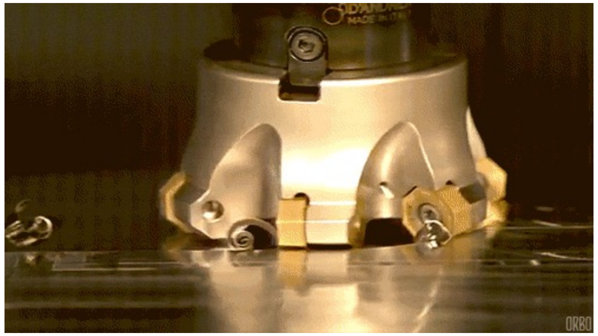
Gamme de fabrication simplifiée

Forgeage → Traitement thermique → Usinage Ebauche



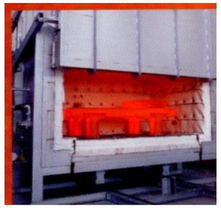


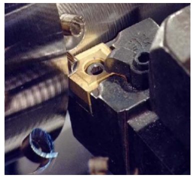


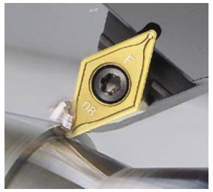


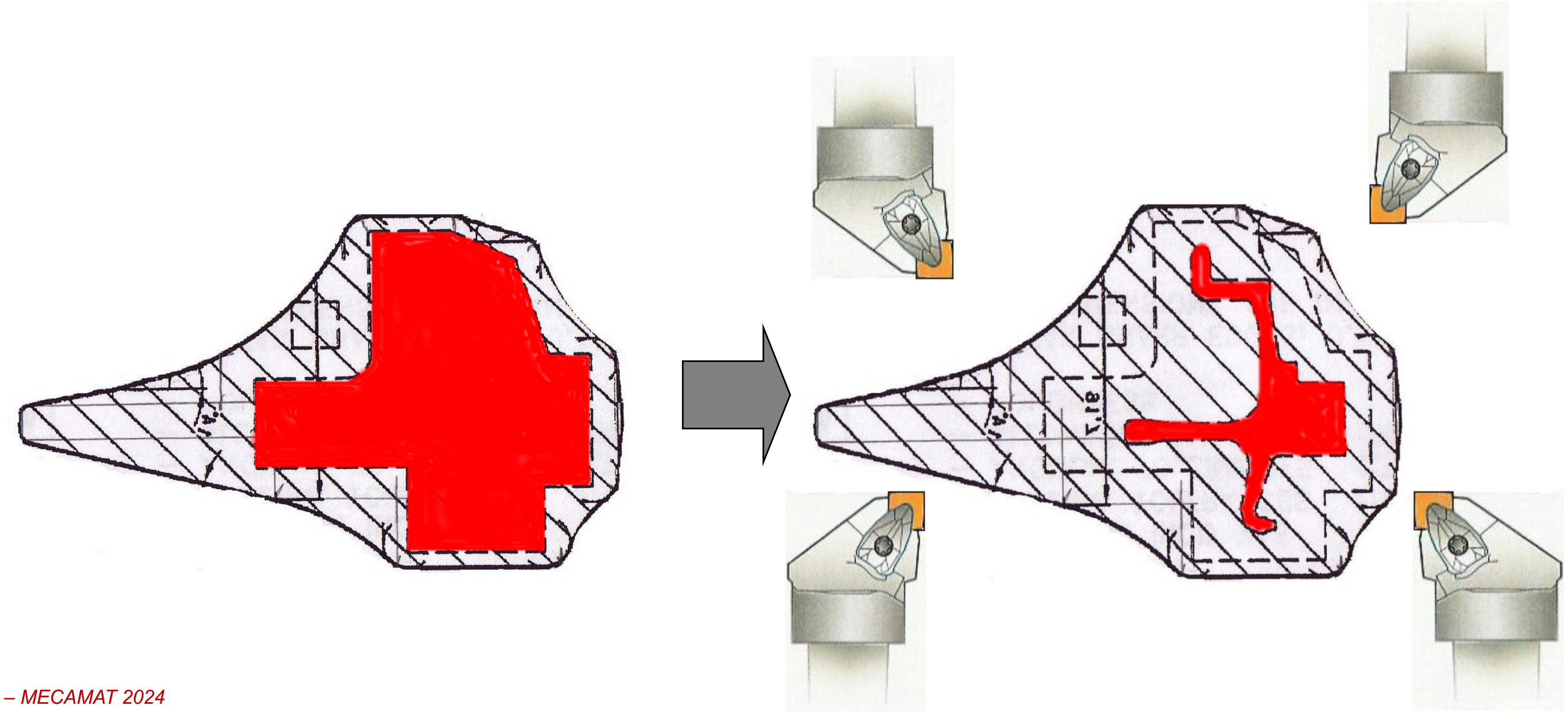
Gamme de fabrication simplifiée

Forgeage → Traitement thermique → Usinage Ebauche → **Usinage Finition**



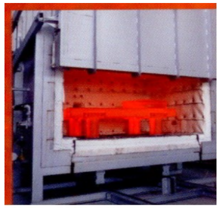


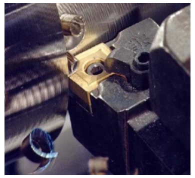


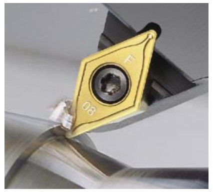


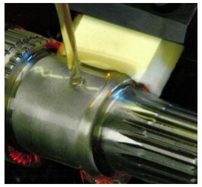
Gamme de fabrication simplifiée

Forgeage → Traitement thermique → Usinage Ebauche → Usinage Finition → Superfinition

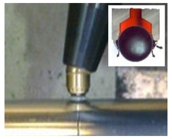




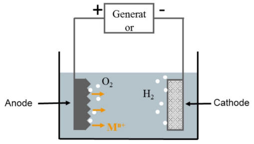




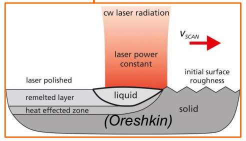
- Abrasion
  - Tribofinishing
  - AFM
  - Sandblasting
  - Brushing
  - Polishing
  - Waterjet
  - Honing
  - Belt finish.
- Plastic Deformat.
  - Shot peening
  - Roller burnis.
- Chemical
  - Acid
  - Electrochem.
- Laser

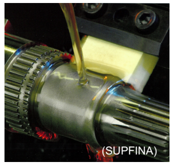


(Soro)



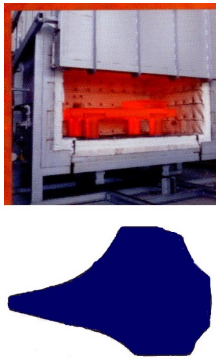
(IRT M2P)

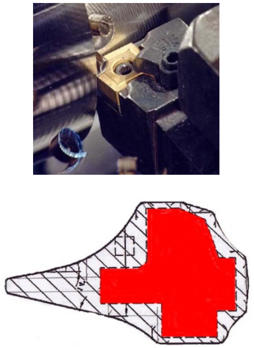


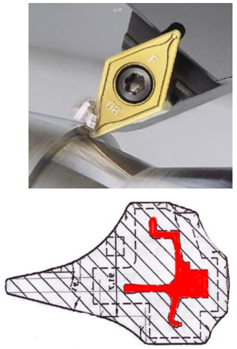


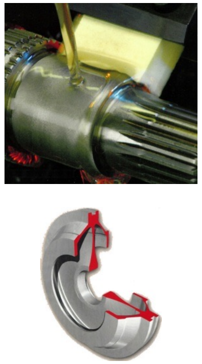
Gamme de fabrication simplifiée

Forgeage → Traitement thermique → Usinage Ebauche → Usinage Finition → Superfinition









?

- → Forces
- → Géométrie
- → Usure d’outils
- → Fragmentation des copeaux

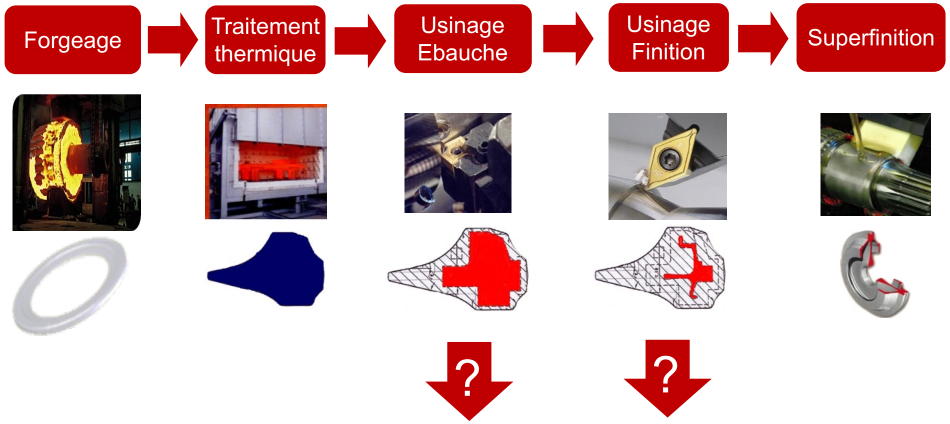
?

- → Forces
- → Géométrie
- → Rugosité
- → Microstructure
- → Contraintes résiduelles
- → Usure d’outils
- → Bavures
- → Fragmentation des copeaux

Besoins industriels

Besoins industriels

- Prédire des indicateurs industriels
- Outils simples / rapides / ergonomiques
- Base de données d'entrée fiables et facile à alimenter
- Traçabilité et Pérennité
- Validation sur un large spectre de situations industrielles (montée en TRL)
- Prise en compte de la variabilité naturelle des conditions de production (usure outils, microstructure)
- Outils doivent s'interfacer dans une chaine numérique globale


Forgeage → Traitement thermique → Usinage Ebauche → Usinage Finition → Superfinition

Usinage Ebauche ?
- ➔ Forces
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- ➔ Usure d'outils
- ➔ Fragmentation des copeaux

Usinage Finition ?
- ➔ Forces
- ➔ Géométrie
- ➔ Rugosité
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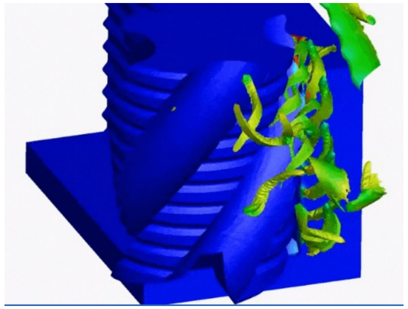
- ➔ Bavures
- ➔ Fragmentation des copeaux

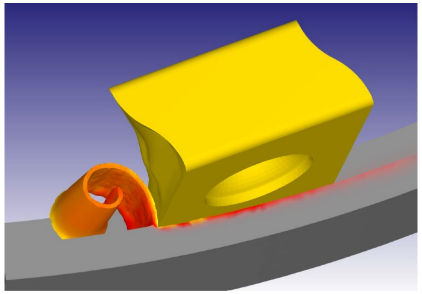
Outils industriels de simulation en usinage

ThirdWave

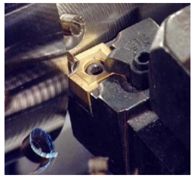


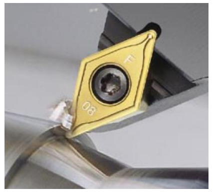
Scientific Forming Technologies Corporation

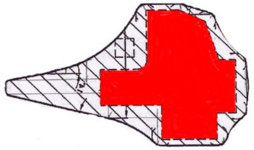
DEFORM
Design Environment for FORMing

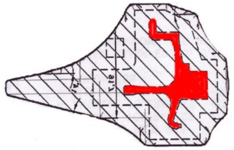


Usinage Ebauche → Usinage Finition









Usinage Ebauche ?

- ➔ **Forces**
- ➔ **Géométrie**
- ➔ **Usure d'outils**
- ➔ **Fragmentation des copeaux**

Usinage Finition ?

- ➔ **Forces**
- ➔ **Géométrie**
- ➔ **Rugosité**
- ➔ **Microstructure**
- ➔ **Contraintes résiduelles**
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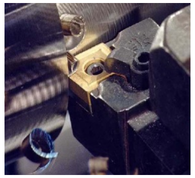
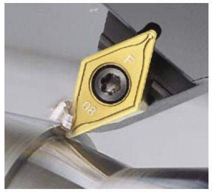
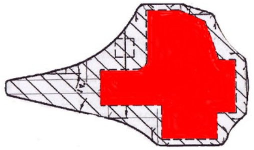
- ➔ **Bavures**
- ➔ **Fragmentation des copeaux**

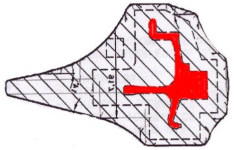
Outils industriels de simulation en usinage

Usinage Ebauche → Usinage Finition









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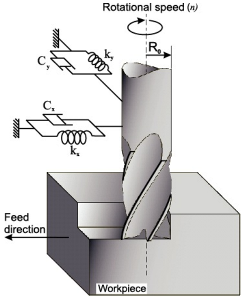
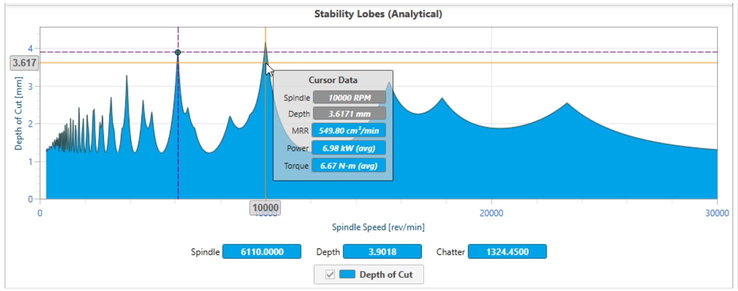
CUTPRO®
Comprehensive Machining Analysis and Chatter Avoidance Optimization Suite





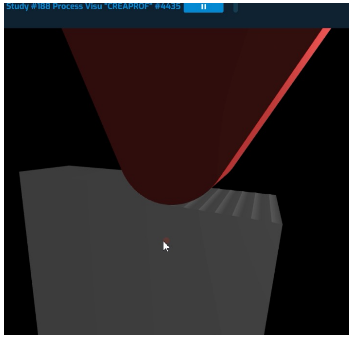
Spindle 10000 RPM
Depth 3.6171 mm
MRR 549.80 cm³/min
Power 6.98 kW (avg)
Torque 6.67 N·m (avg)

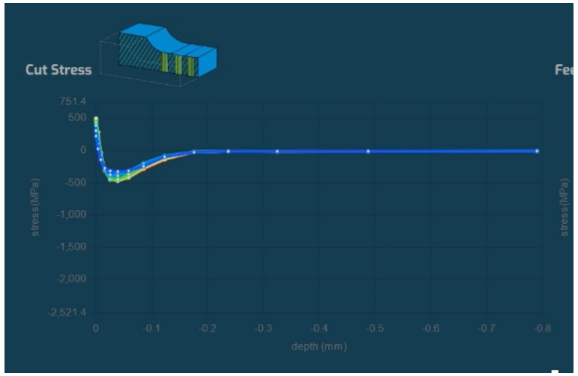
Spindle 6110.0000 Depth 3.9018 Chatter 1324.4500

☑ Depth of Cut

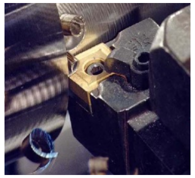
Outils industriels de simulation en usinage

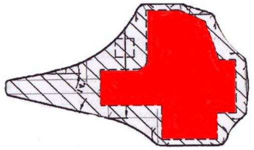
MISULAB





Usinage Ebauche → Usinage Finition





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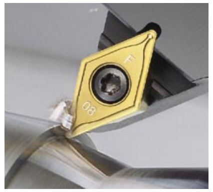
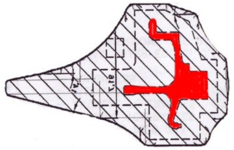
- ➔ Fragmentation des copeaux





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- ➔ Bavures
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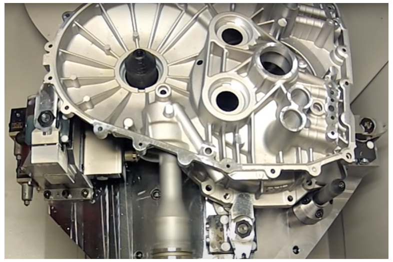
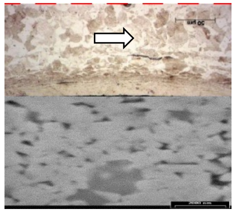
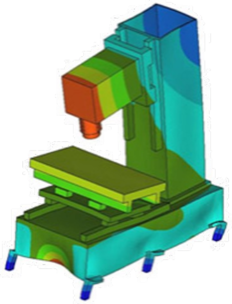
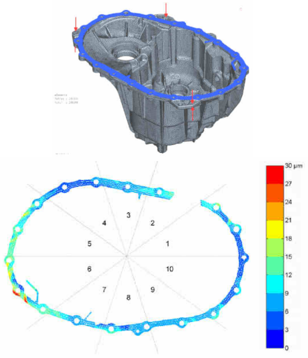
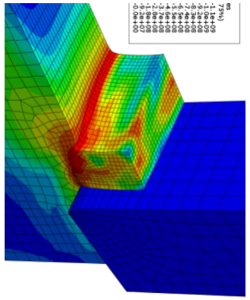
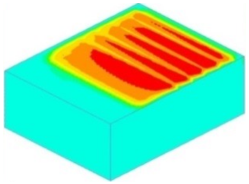
Echelle de modélisation

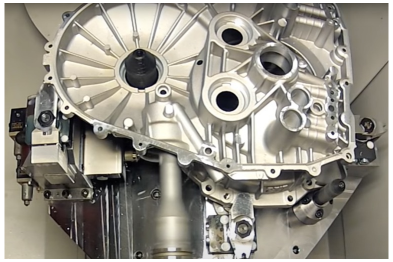


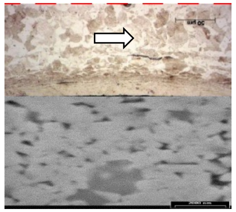
Machine → Pièce / Outil → Enlèvement de matière → Surfaces

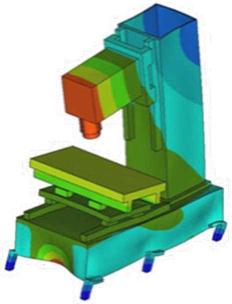
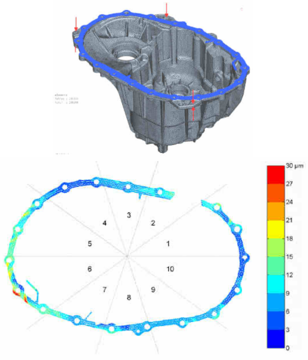
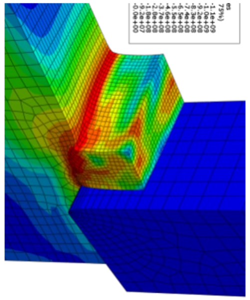
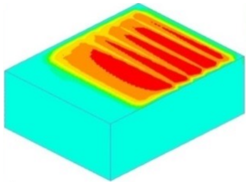





Echelle 1 000 000 μm 100 000 μm 1 000 μm 10 μm

Outils industriels de simulation en usinage

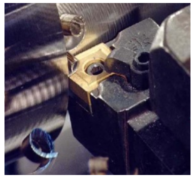



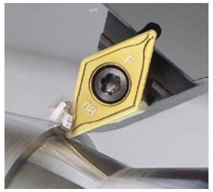


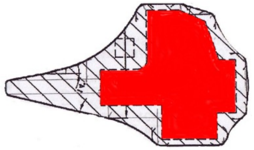
Machine	Pièce / Outil	Enlèvement de matière	Surfaces
			
	CUTPRO® Comprehensive Machining Analysis and Chatter Avoidance Optimization Suite	DEFORM® Design Environment for FORMing	
		ThirdWave	
		MISULAB	MISULAB

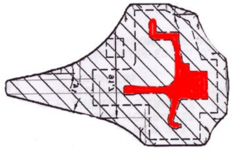
Les réponses aux besoins industriels

Usinage Ebauche → Usinage Finition









?

- → Forces
- → Géométrie
- → Usure d’outils
- → Fragmentation des copeaux

?

- → Forces
- → Géométrie
- → Rugosité
- → Microstructure
- → Contraintes résiduelles
- → Usure d’outils
- → Bavures
- → Fragmentation des copeaux

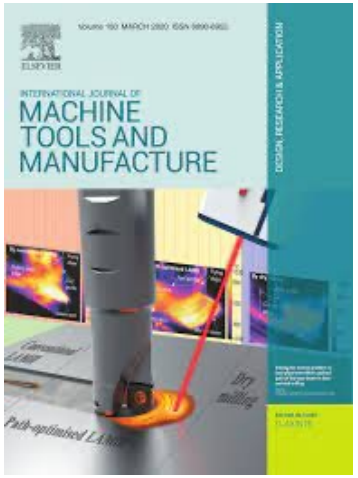
🟦 Réponses partielles

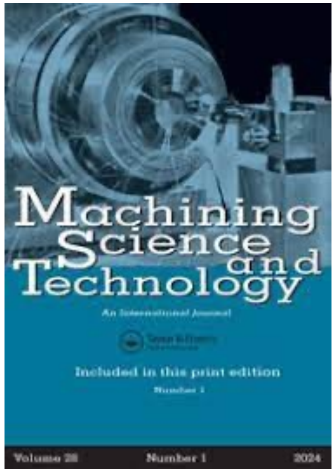
🟥 Rien

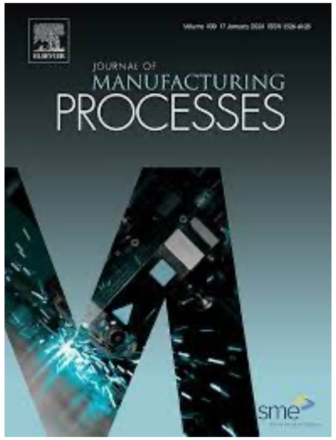
Les recherches académiques en usinage

ScienceDirect

Mots clefs : Cutting / Modeling / Simulation → 20.000 articles







Les recherches académiques en usinage

Conférences dédiées à la simulation

KIT Karlsruhe Institute of Technology

19TH CIRP CONFERENCE

on Modeling of Machining Operations

31st May – 02nd June 2023 | Karlsruhe, Germany

ISF

wbk

Conférences Métiers
(incluant une session simulation)

17th INTERNATIONAL CONFERENCE

HIGH SPEED MACHINING

SUSTAINABILITY AND HIGH PERFORMANCE IN MACHINING

25—28/10 2023 NANJING | CHINA

HPC'18 8th CIRP Conference on High Performance Cutting

Conférences généralistes
(incluant une session simulation)

ESAFORM

19–21 April 2023

KRAKÓW

Les recherches académiques en usinage

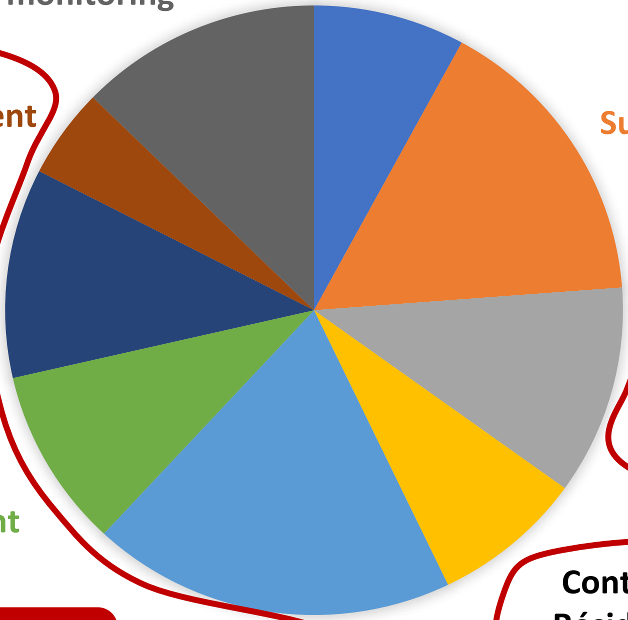
KIT

19TH CIRP CONFERENCE on Modeling of Machining Operations

31st May – 02nd June 2023 | Karlsruhe, Germany

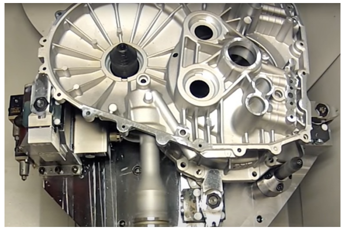
ISF wbk

80 articles

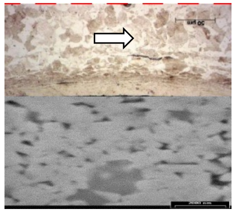


Enlèvement de matière

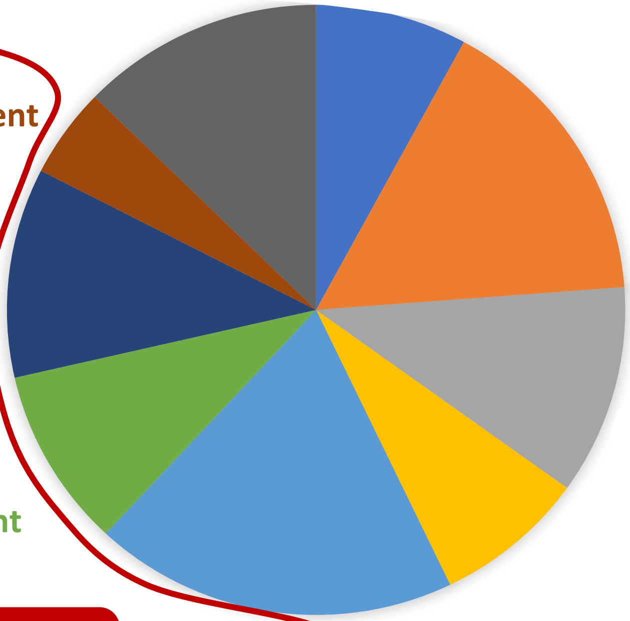
Pièce / Outil



Surfaces

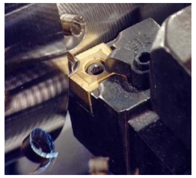


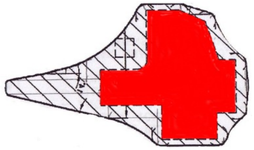
Les recherches académiques en usinage

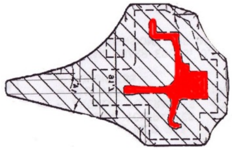


Enlèvement de matière

Usinage Ebauche → **Usinage Finition**







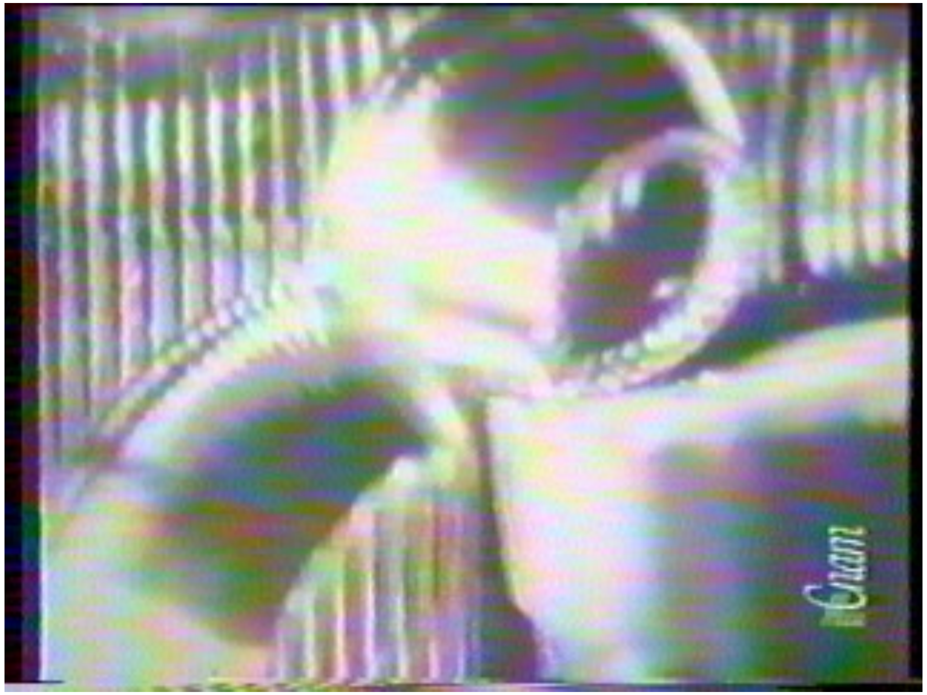
?

- → **Forces**
- → **Fragmentation des copeaux**

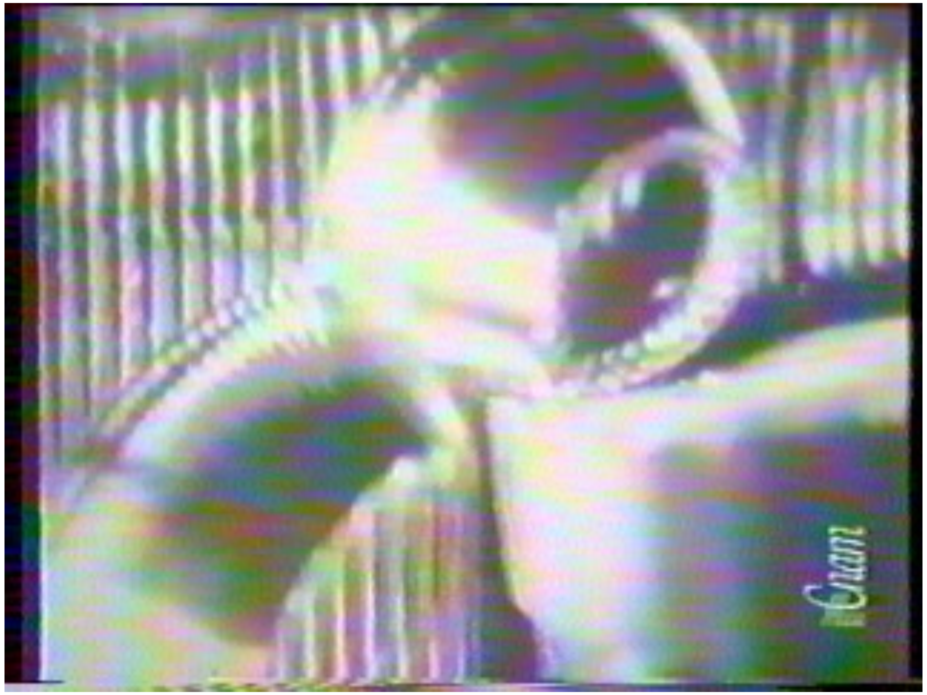
?

- → **Forces**
- → **Fragmentation des copeaux**

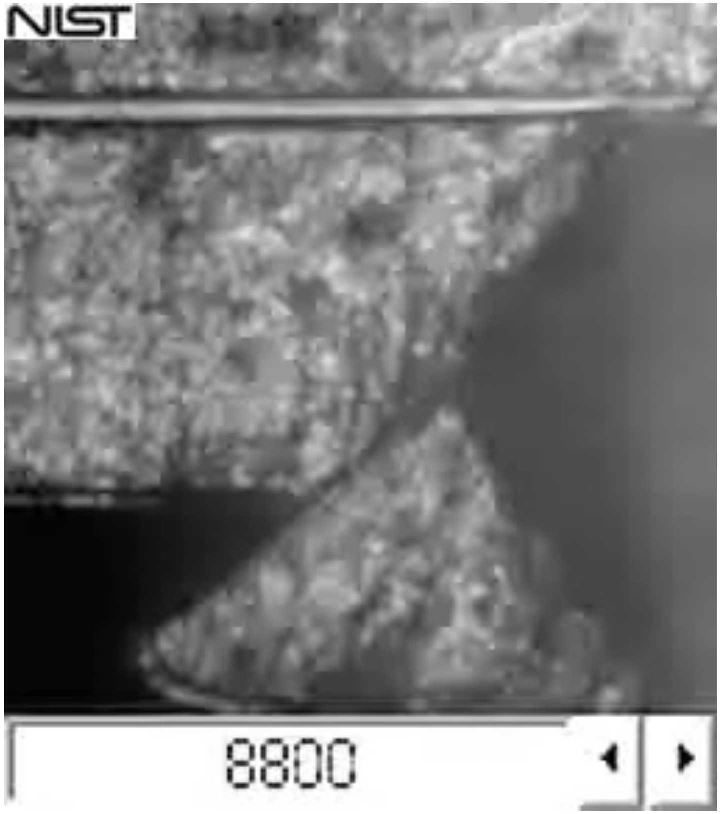
Enlèvement de matière



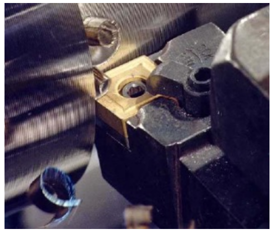
Enlèvement de matière

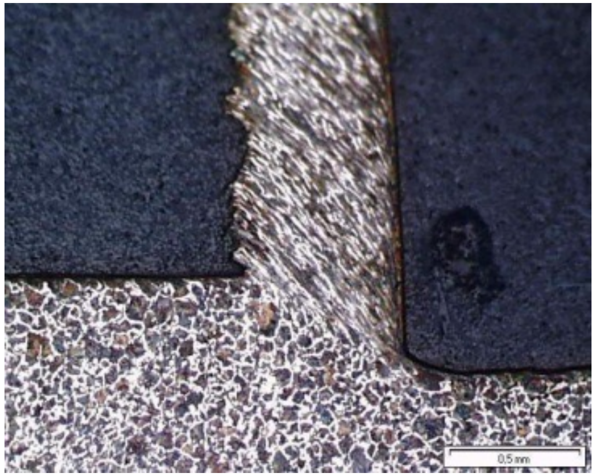


Festonnage

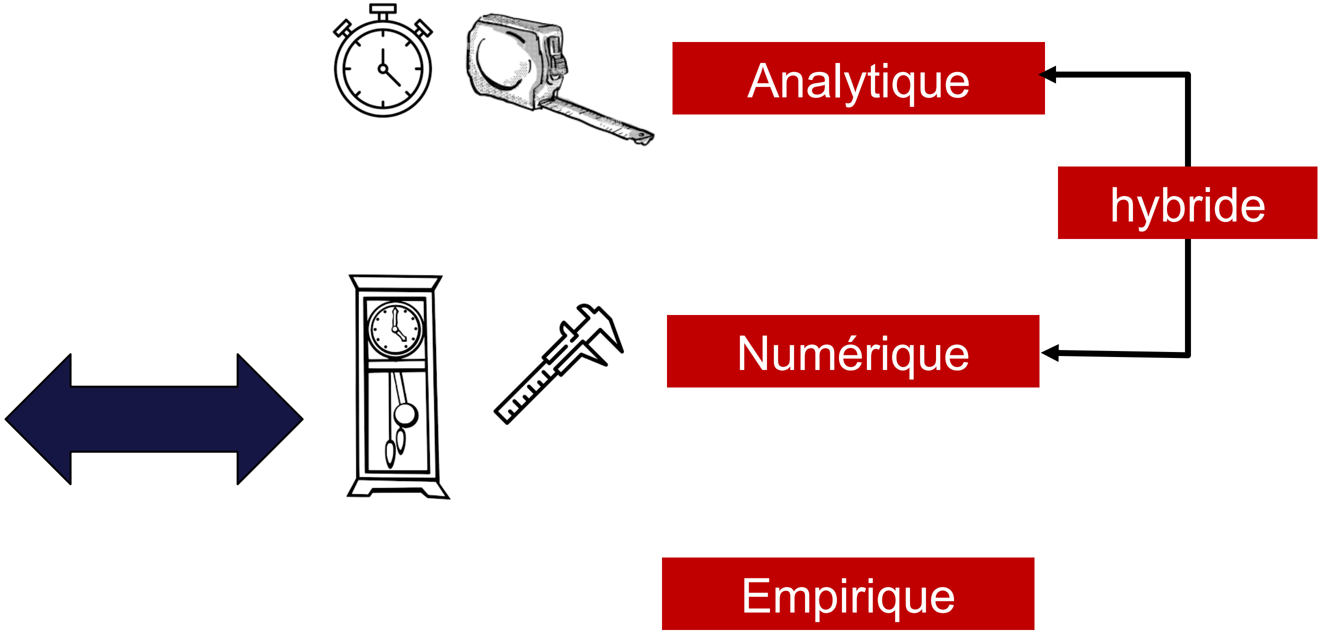


Modélisation de l’enlèvement de matière





Acier 27MnCr5
180 HB
Vc=120 m/min
f =0,2 mm/rev



Analytique

hybride

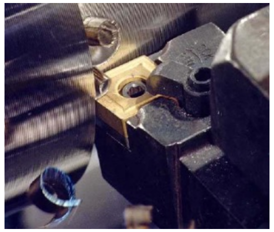
Numérique

Empirique

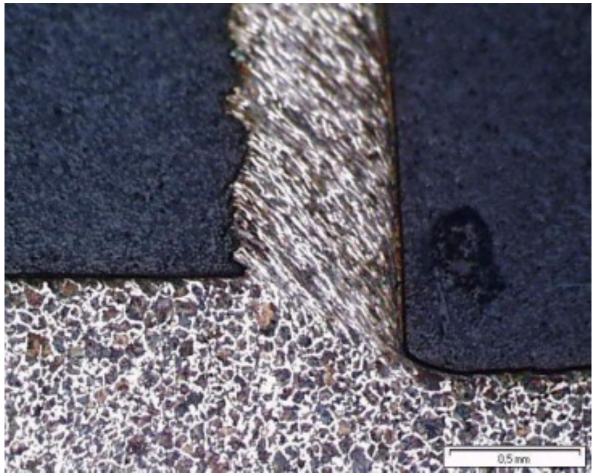
Modélisation de l'enlèvement de matière

2 D

3 D



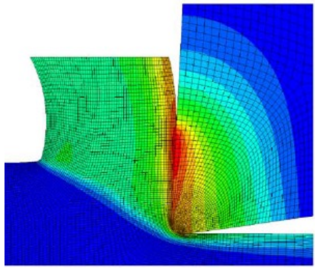
Acier 27MnCr5
180 HB
Vc=120 m/min
f =0,2 mm/rev

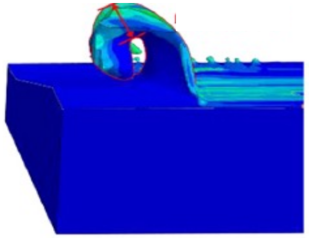


Numérique

ALE / CEL

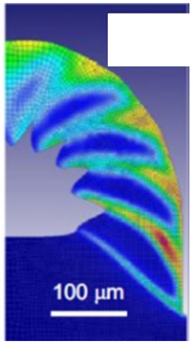
Explicit

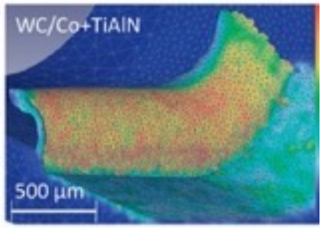




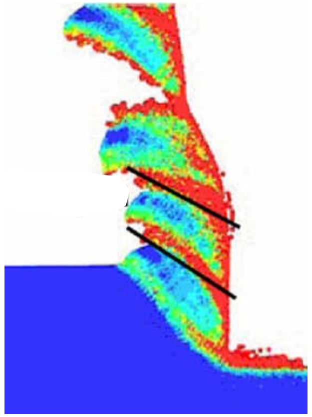
Lagrang.

Explicit

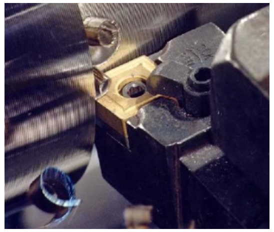




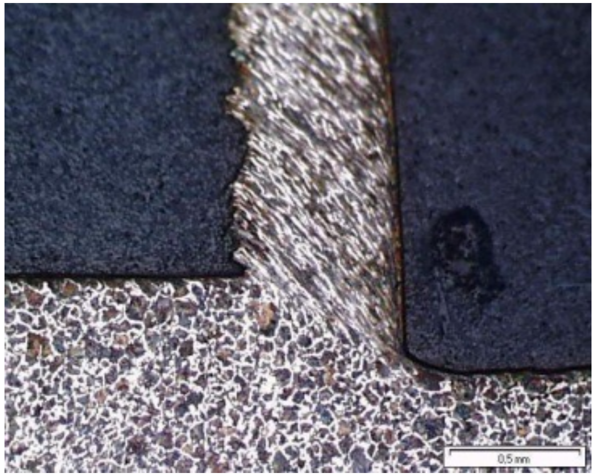
SPH



Modélisation de l'enlèvement de matière



Acier 27MnCr5
180 HB
Vc=120 m/min
f =0,2 mm/rev

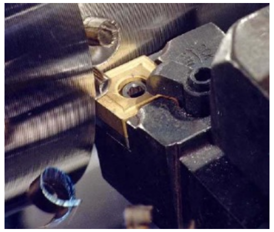


Numérique

	2 D	3 D
ALE / CEL Explicit	MISULAB	
Lagrang. Explicit		ThirdWave DEFORM® Design Environment for FORMing
SPH		

Modélisation de l'enlèvement de matière

Modèles 2.5 D



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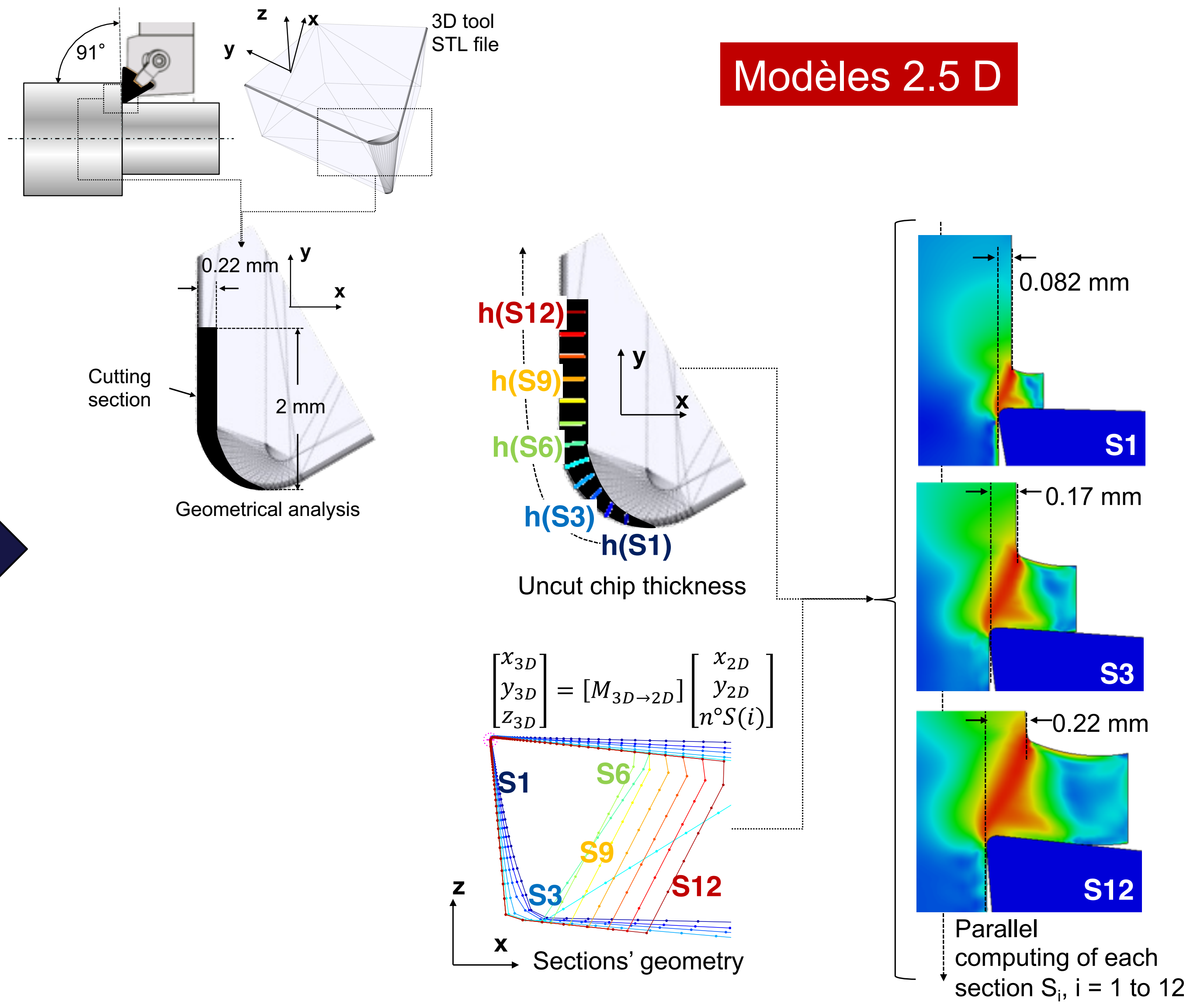


$$\begin{bmatrix}x_{3D}\\ y_{3D}\\ z_{3D}\end{bmatrix} = [M_{3D\rightarrow 2D}]\begin{bmatrix}x_{2D}\\ y_{2D}\\ n°S(i)\end{bmatrix}$$

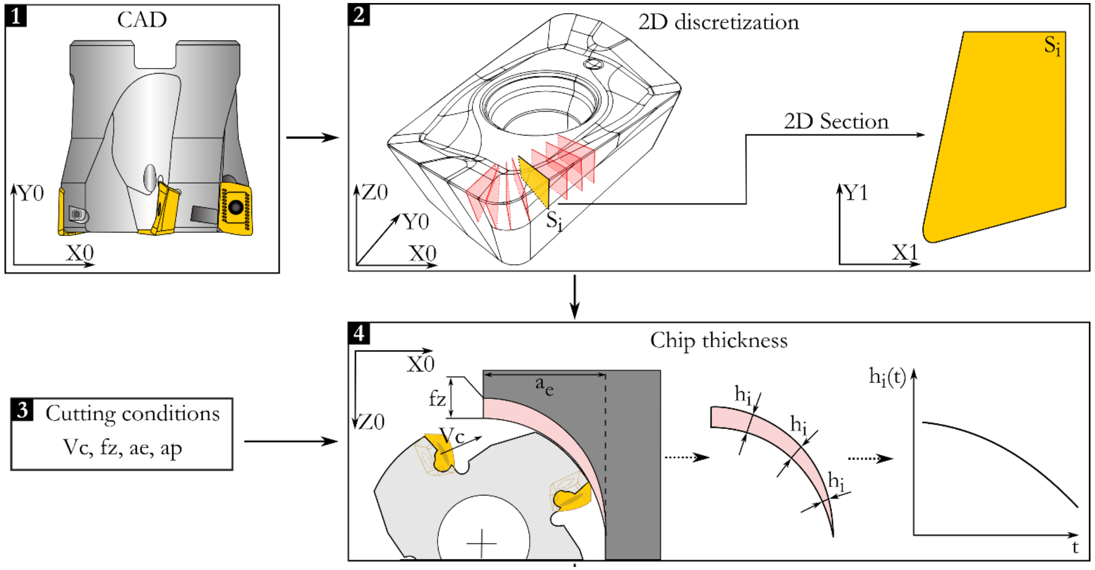
Parallel computing of each section S_i, i = 1 to 12

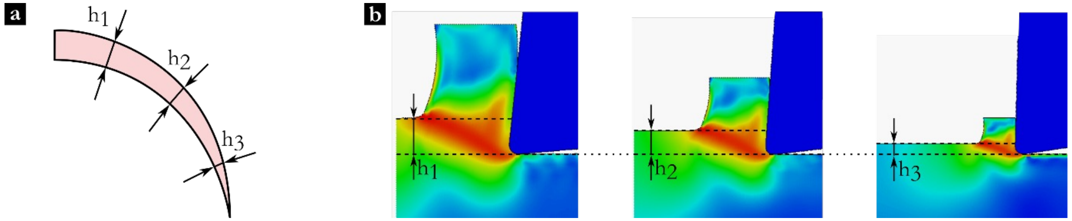
Courbon et al. (2020)

Modélisation de l'enlèvement de matière

Modèles 2.5 D + Temps

Numérique





Méthon et al. (2023)

Modélisation de l'enlèvement de matière

GEOMETRIE

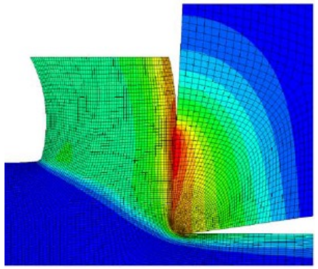
LOI D'ECOULEMENT

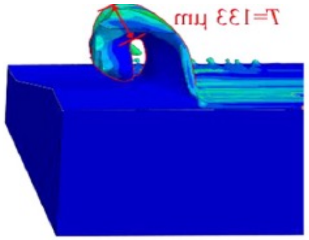
LOI D'ENDOMMAGEMENT

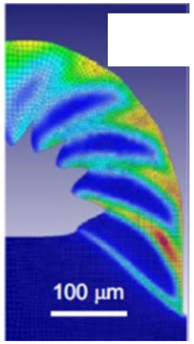
FROTTEMENT / USURE

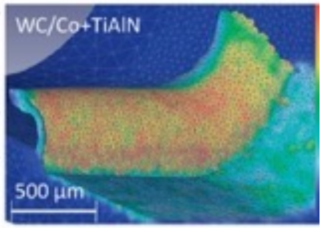
ECHANGE THERMIQUE

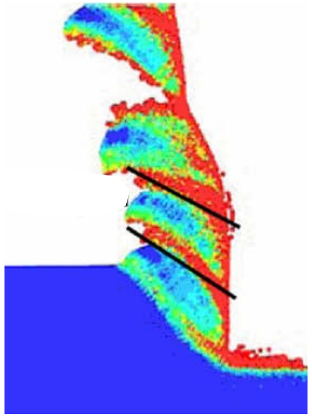
PROPRIETES THERMIQUES





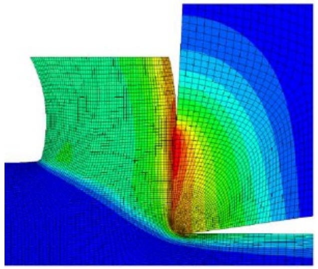


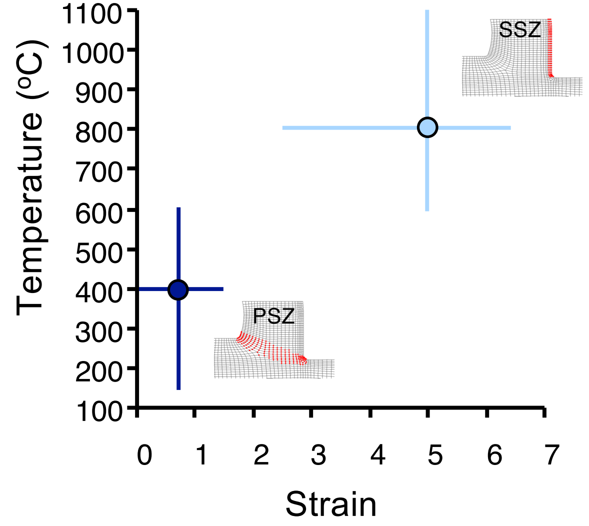


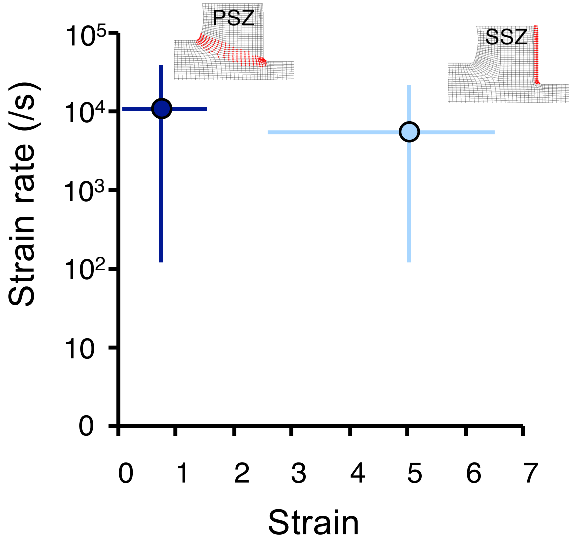


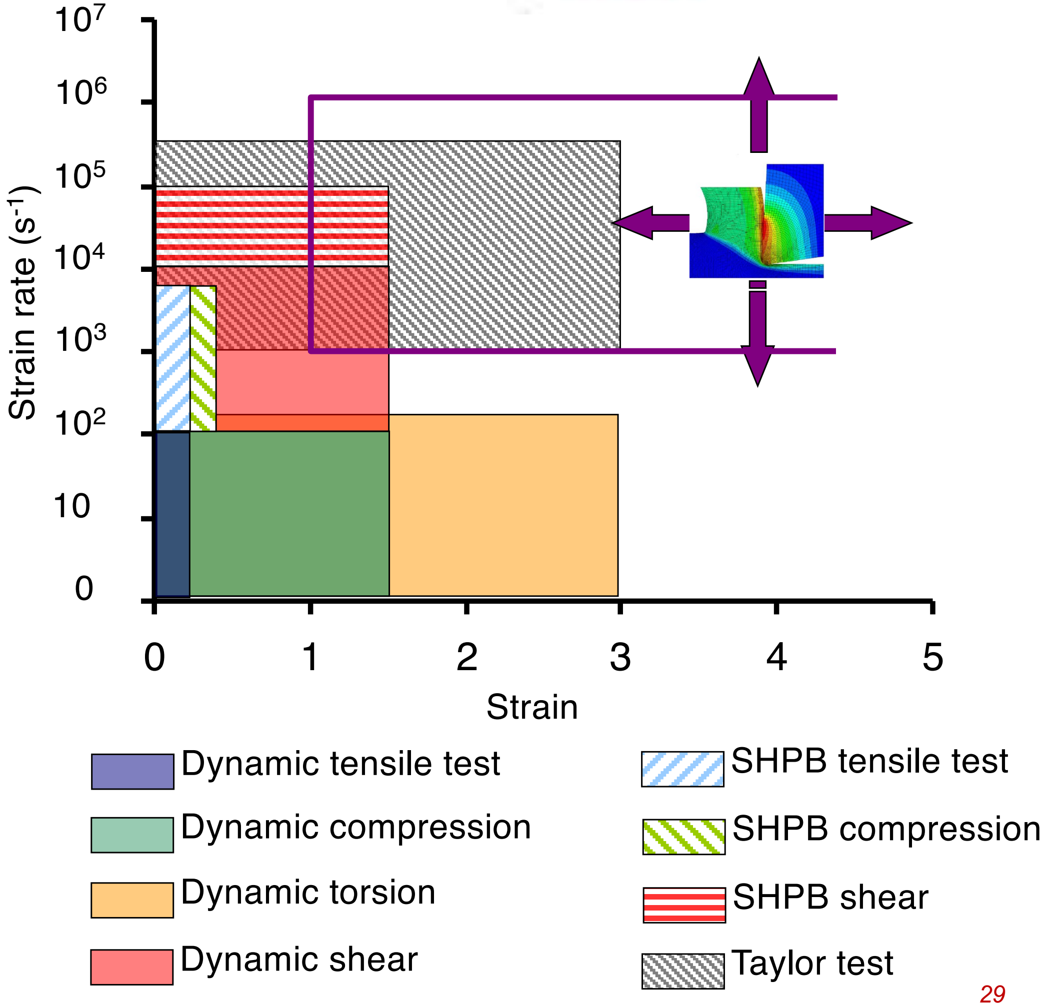
Données d'entrée des modèles

LOI D'ECOULEMENT





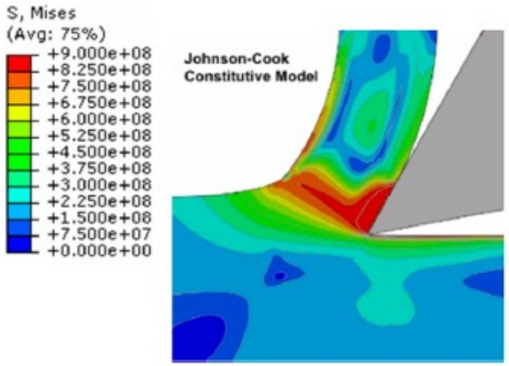




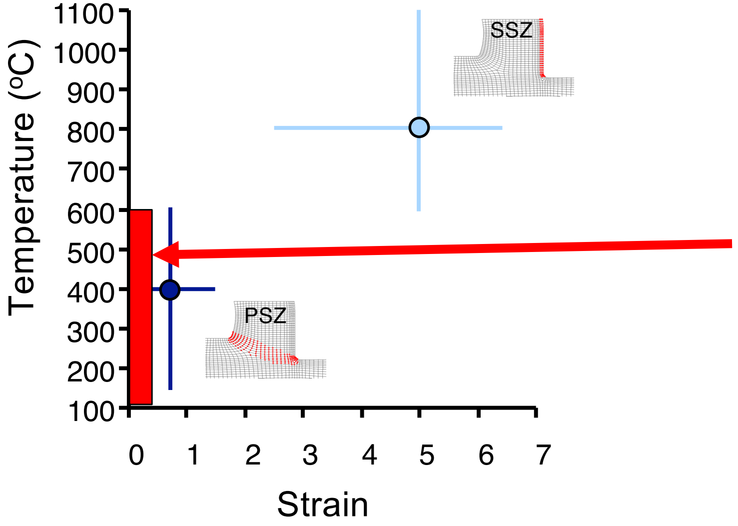
Courbon et al. (2008)

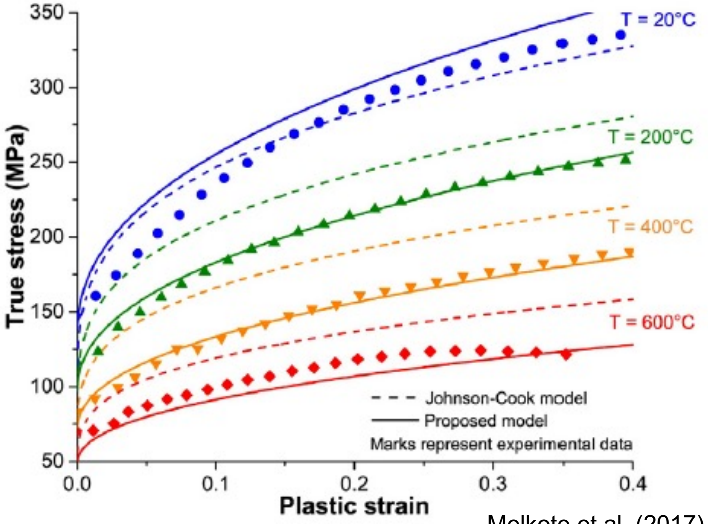
Données d’entrée des modèles

LOI D’ECOULEMENT



Cuivre





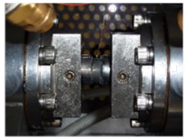
Melkote et al. (2017)

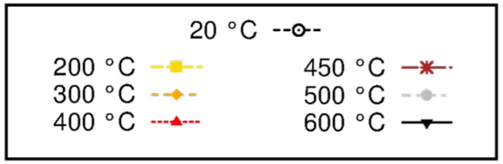
$$\bar{\sigma} = \left[A + B\left(\bar{\varepsilon}\right)^{n}\right]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^{m}\right]$$

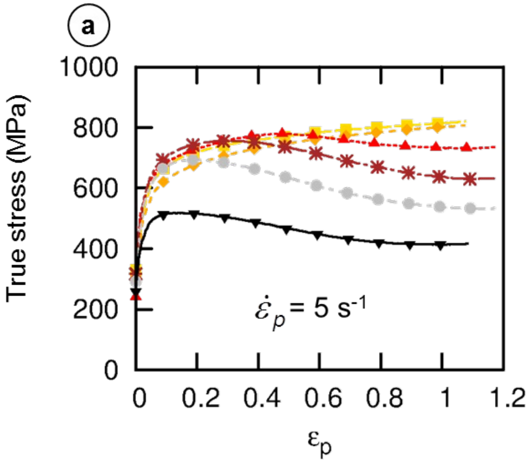
Johnson – Cook constitutive model

Données d’entrée des modèles

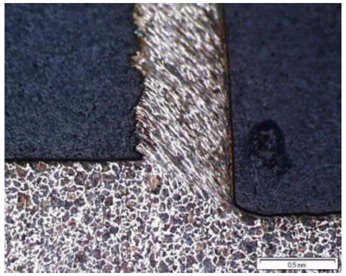
LOI D’ECOULEMENT

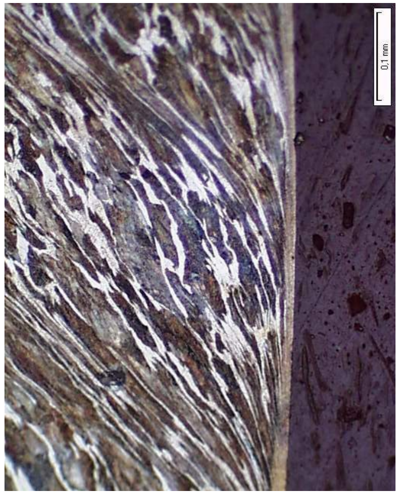


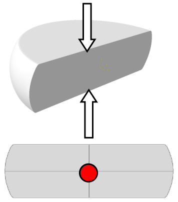


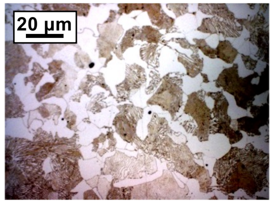


Acier 1045

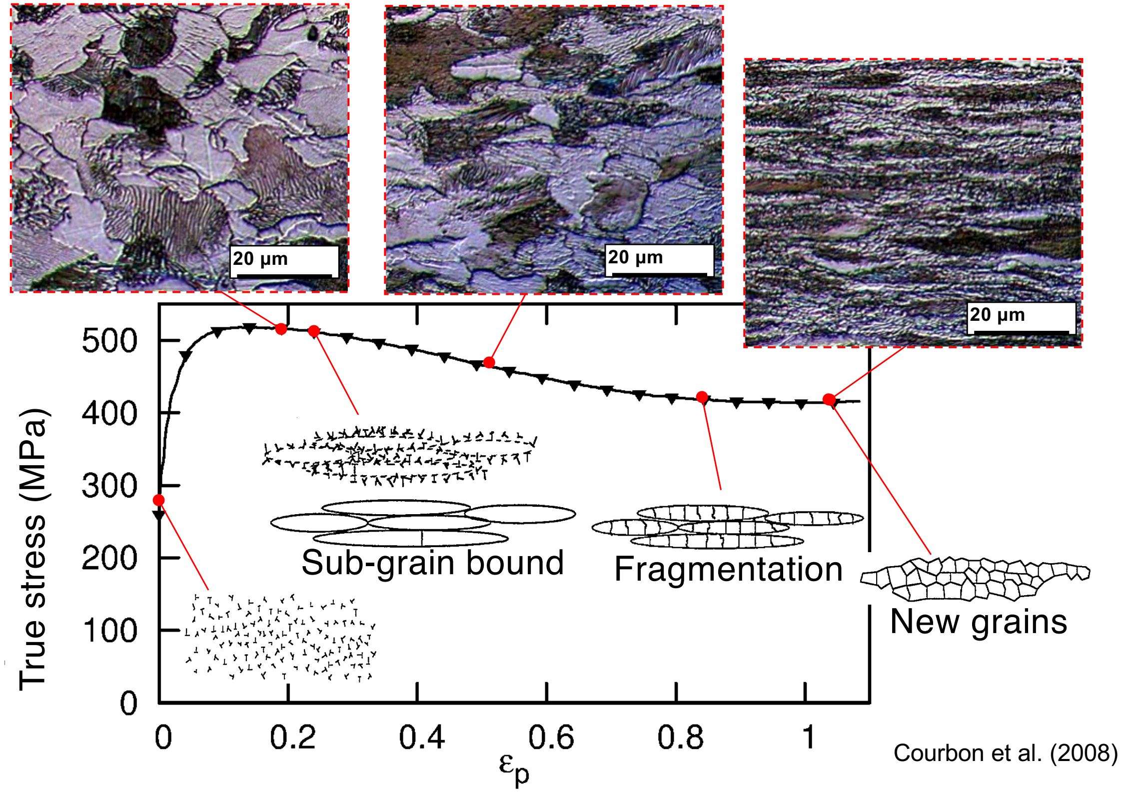








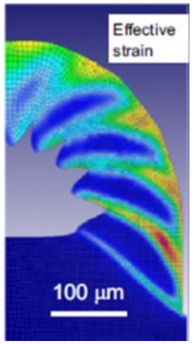
Initial state

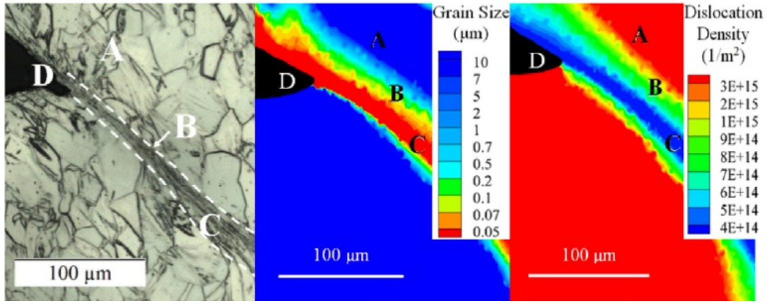


Courbon et al. (2008)

Données d'entrée des modèles

LOI D'ENDOMMAGEMENT



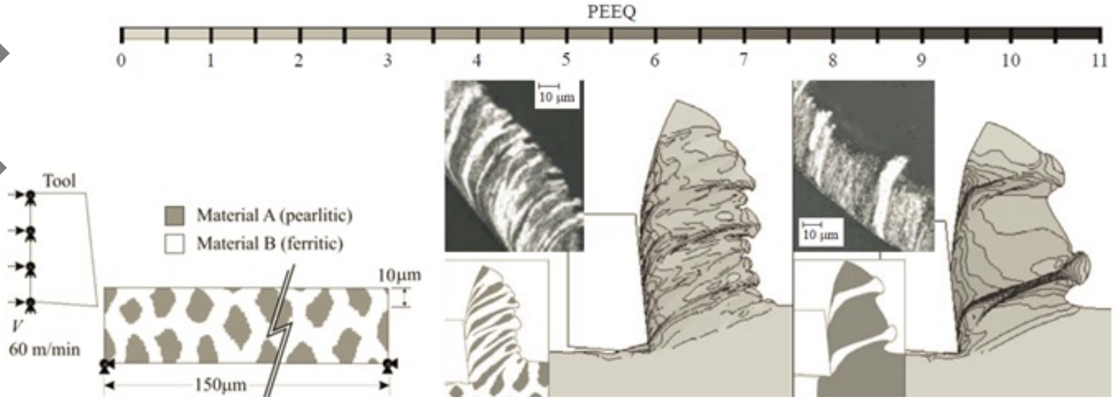


Melkote et al. (2017)

Données d'entrée des modèles

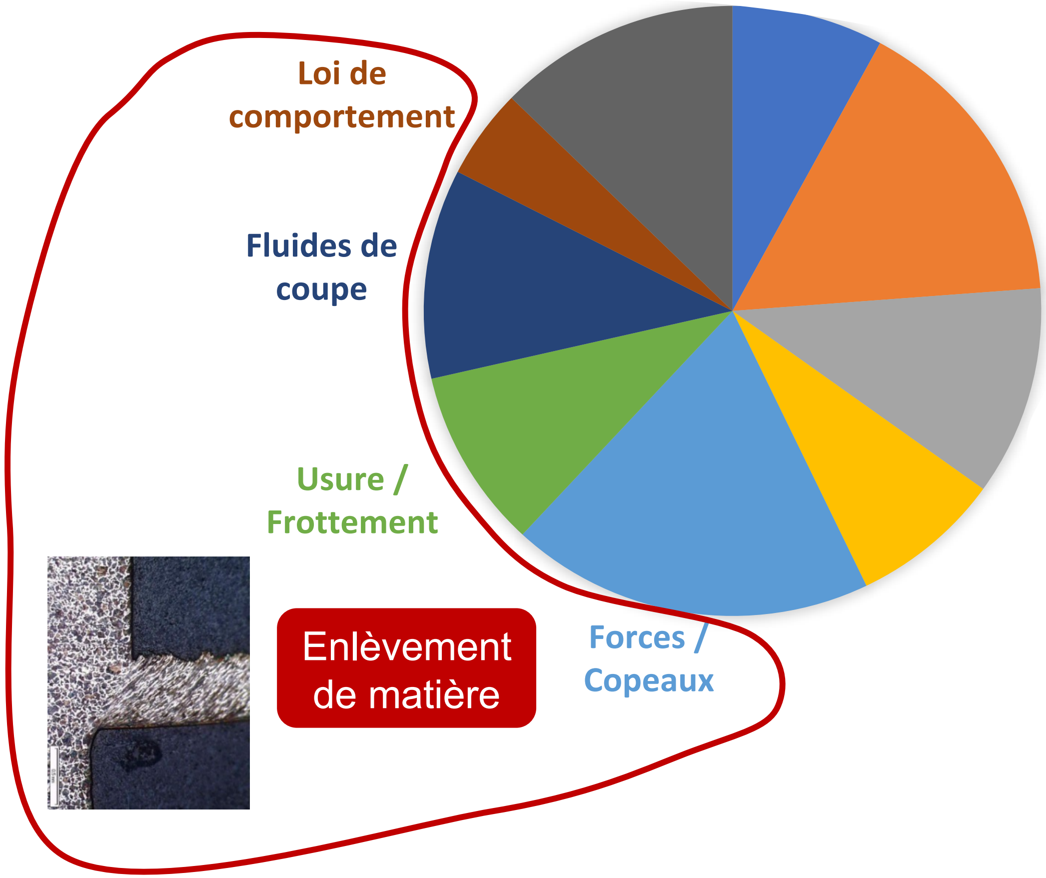
MATERIAU HETEROGENE

MICRO USINAGE



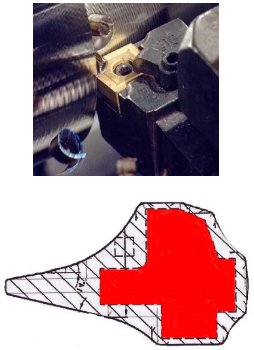
Simoneau & Elbastawi [2007]

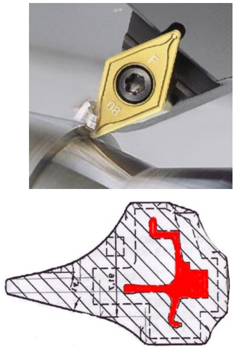
Les recherches académiques en usinage



Enlèvement de matière

Usinage Ebauche → **Usinage Finition**





?

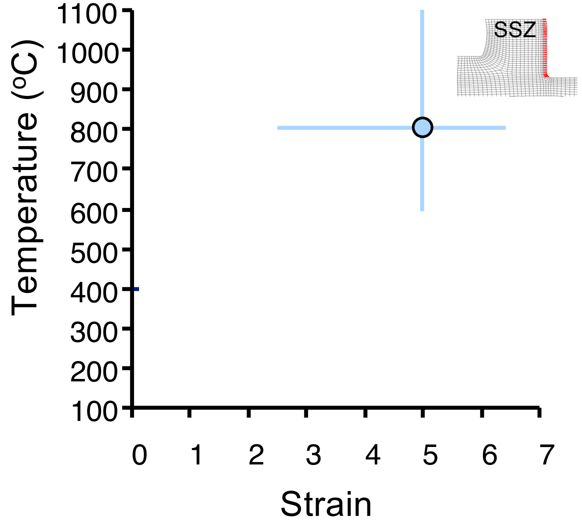
→ **Usure d'outils**

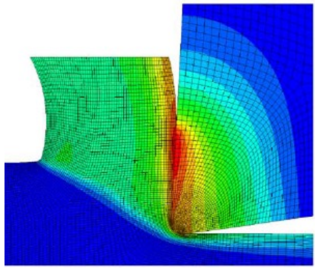
?

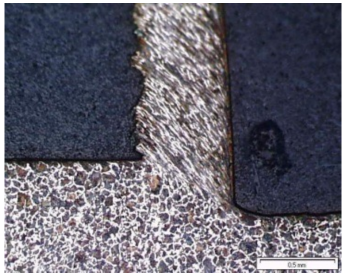
→ **Usure d'outils**

Interfaces : Frottement / Usure

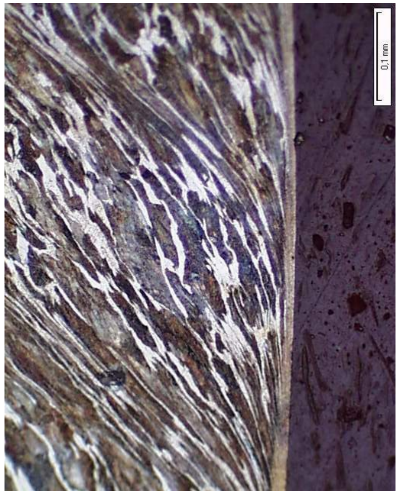
LOI DE FROTTEMENT

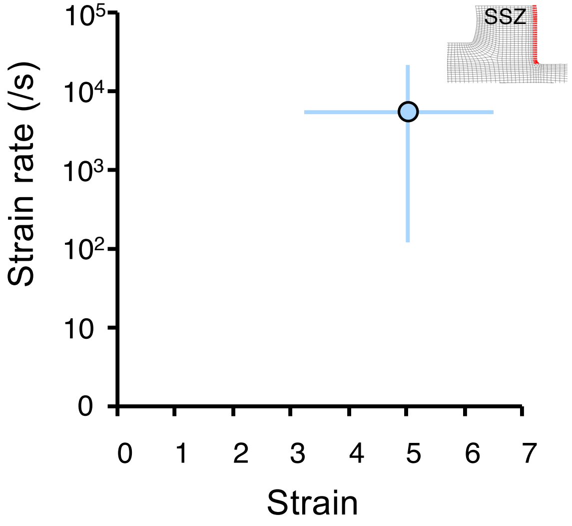


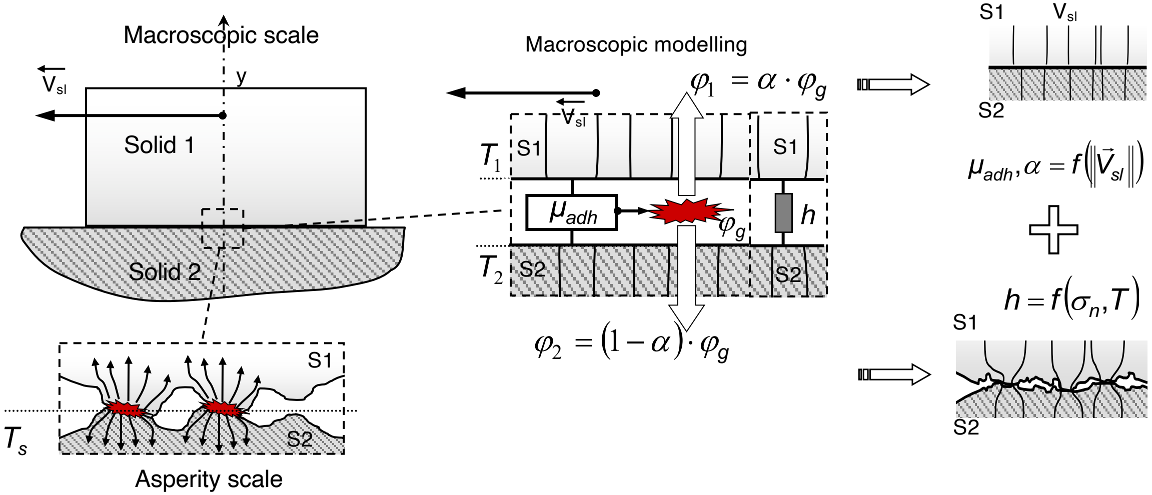




Acier 27MnCr5
180 HB
Vc=120 m/min
f =0,2 mm/rev



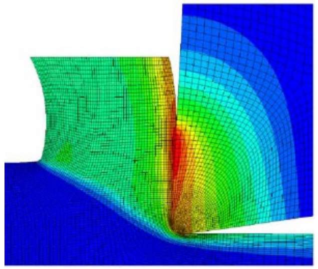


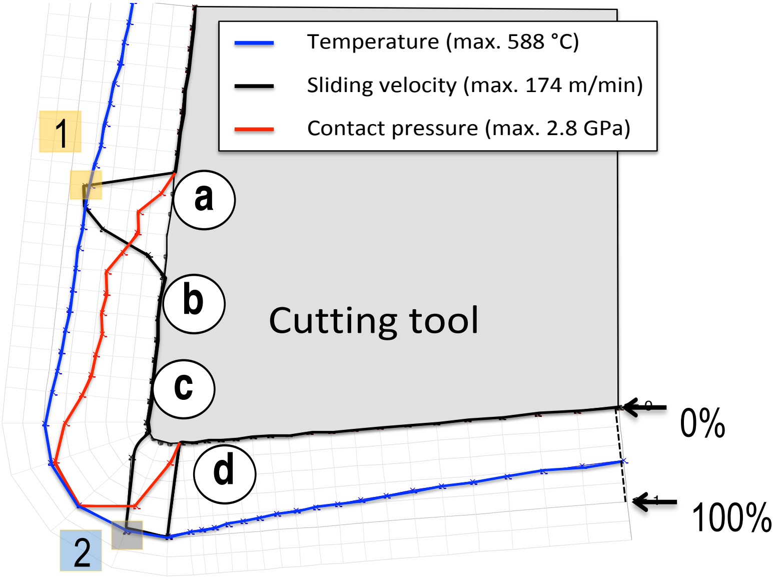


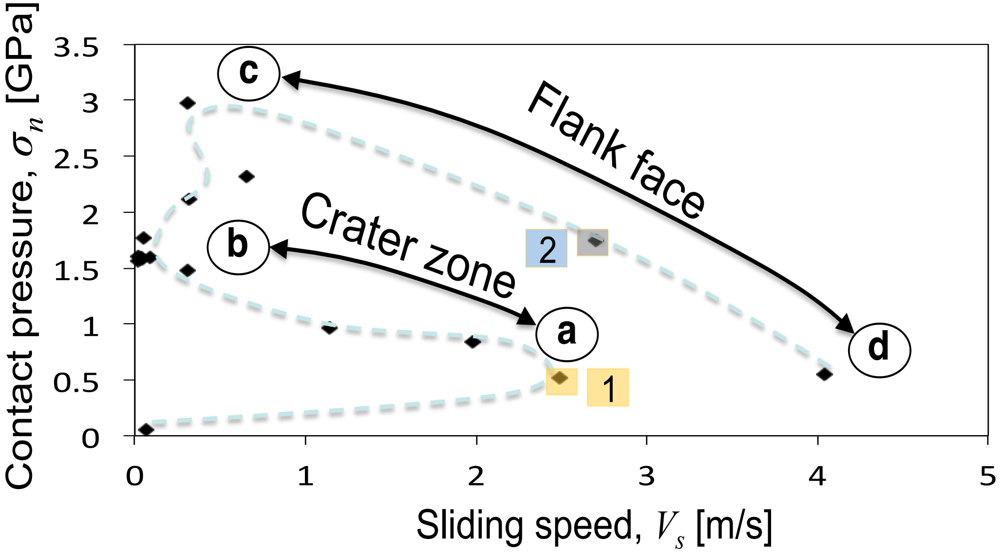
Courbon et al. (2008)

Interfaces : Frottement / Usure

LOI DE FROTTEMENT

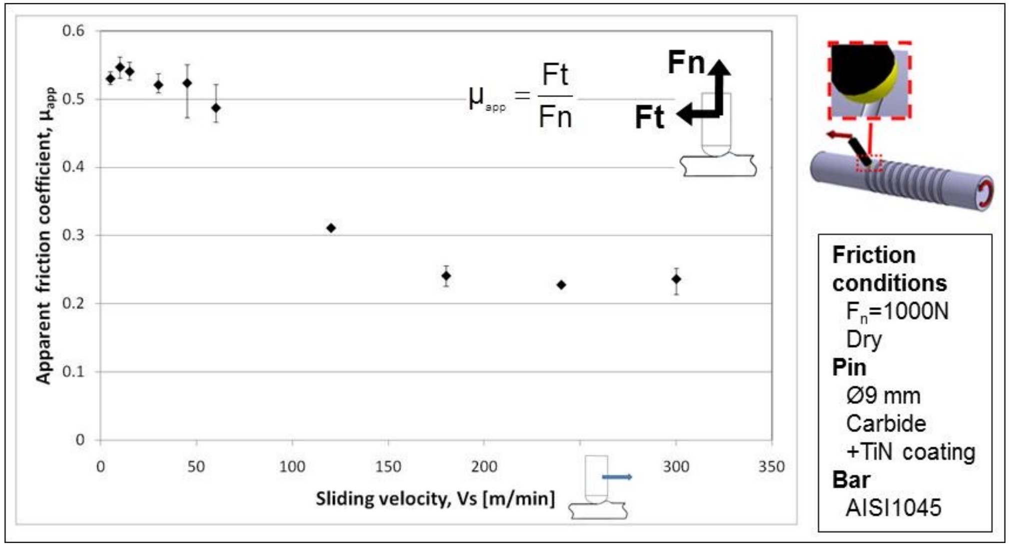






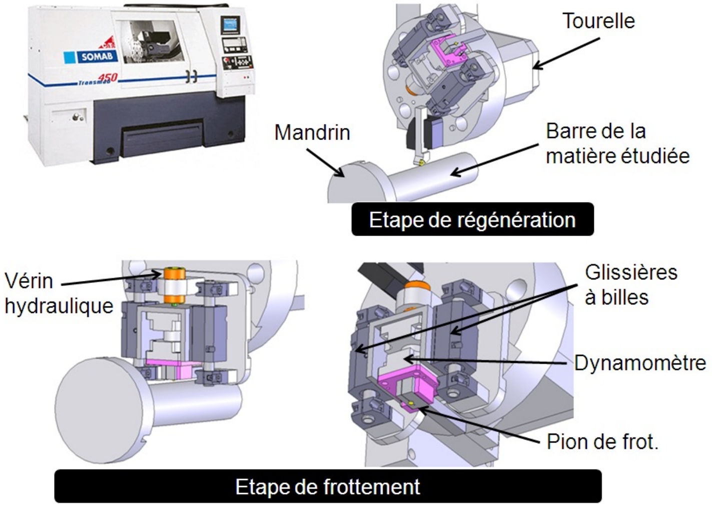
Interfaces : Frottement / Usure

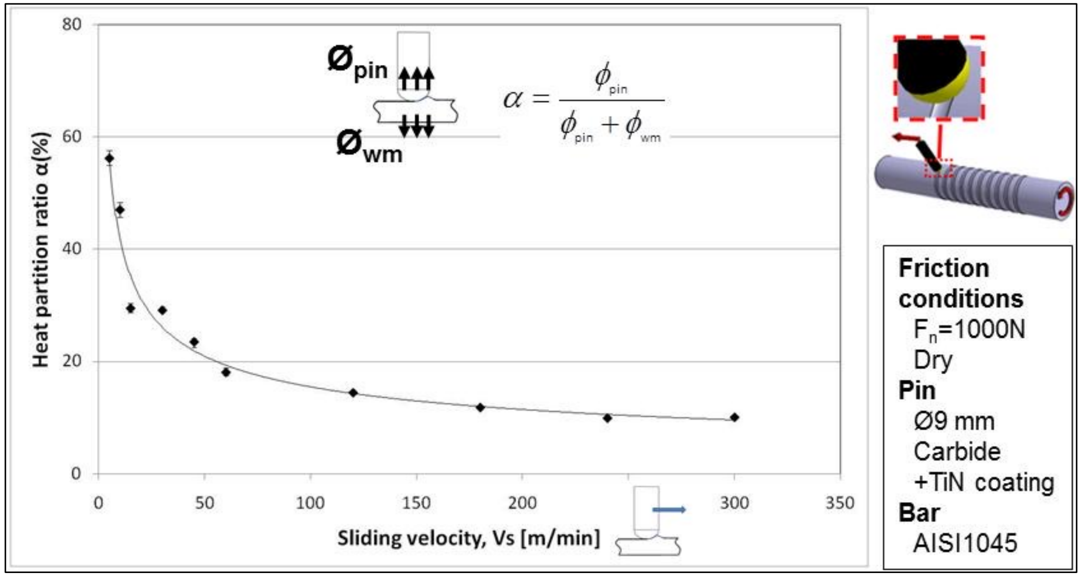
LOI DE FROTTEMENT → Utilisation de tribomètres dédiés



$\mu_{app} = \frac{Ft}{Fn}$

Friction conditions
F_n=1000N
Dry
Pin
Ø9 mm
Carbide
+TiN coating
Bar
AISI1045



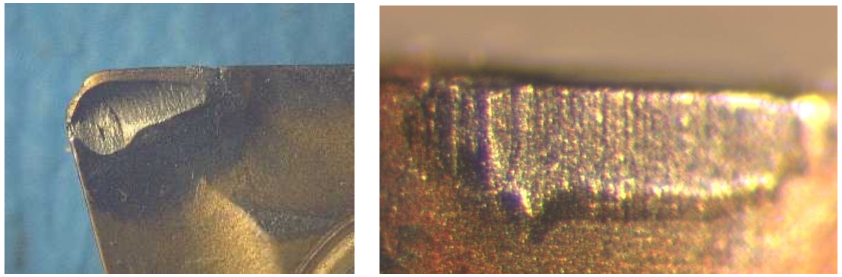


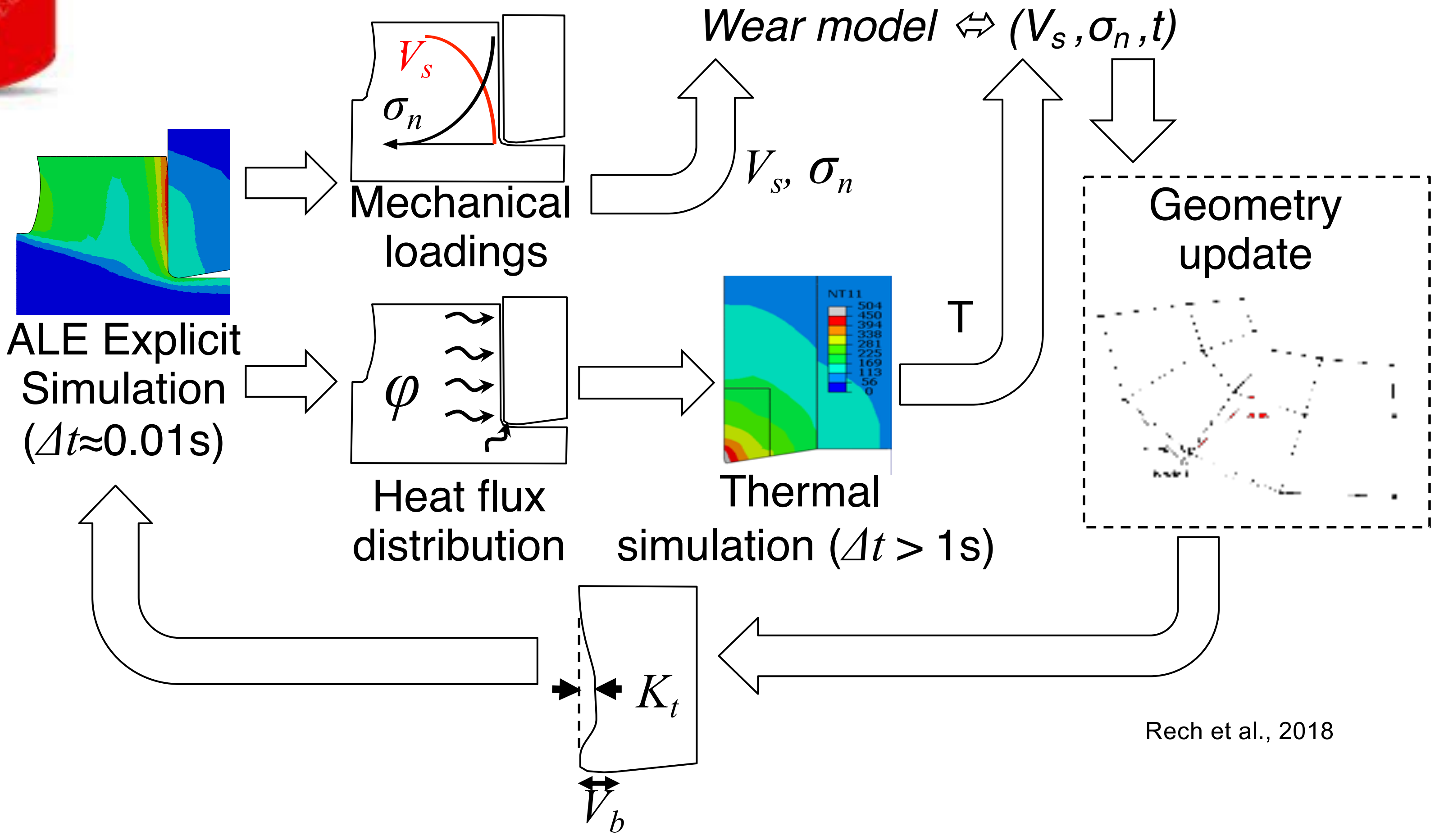
$\alpha = \frac{\phi_{pin}}{\phi_{pin} + \phi_{wm}}$

Friction conditions
F_n=1000N
Dry
Pin
Ø9 mm
Carbide
+TiN coating
Bar
AISI1045

Interfaces : Frottement / Usure

LOI D'USURE





Wear model ⇔ (V_s, σ_n, t)

ALE Explicit Simulation ($\Delta t \approx 0.01$s)

Mechanical loadings

V_s, σ_n

Heat flux distribution

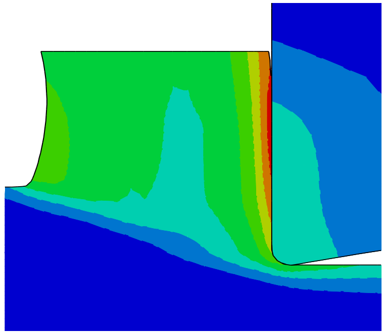
Thermal simulation ($\Delta t > 1$s)

T

Geometry update

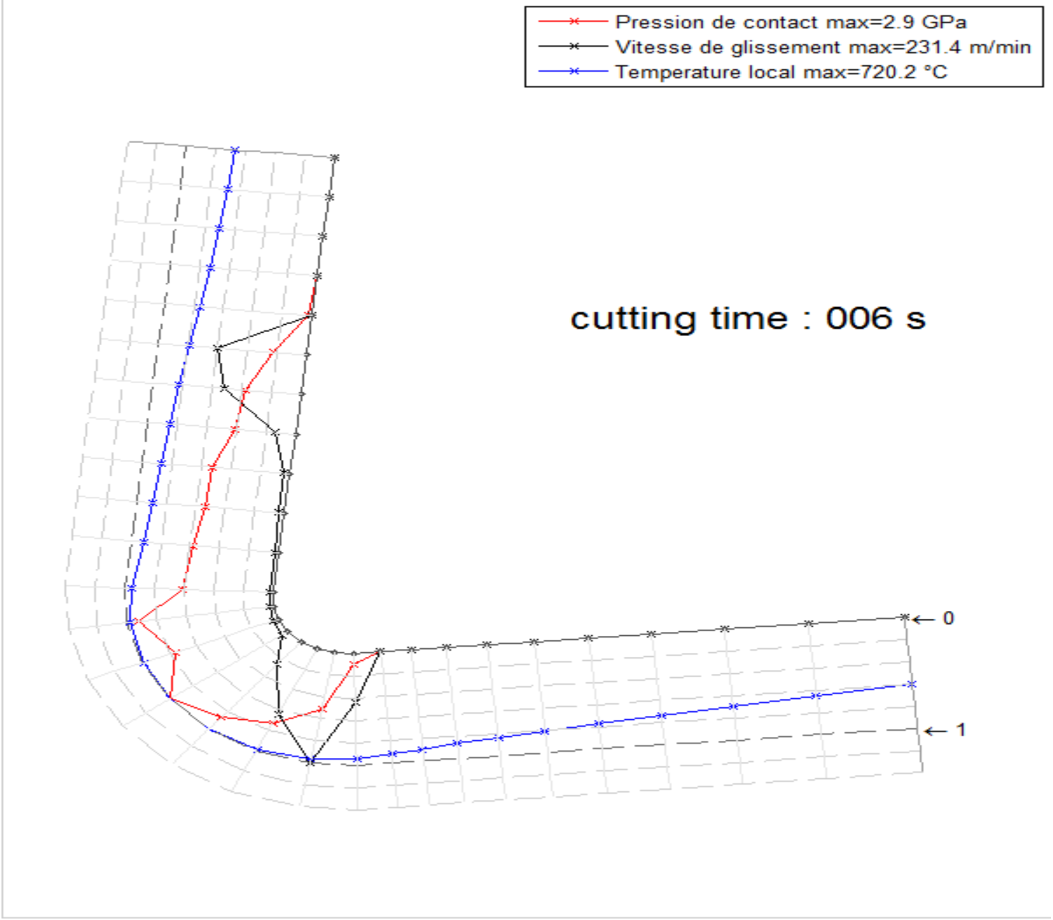
Rech et al., 2018

Usure des outils de coupe

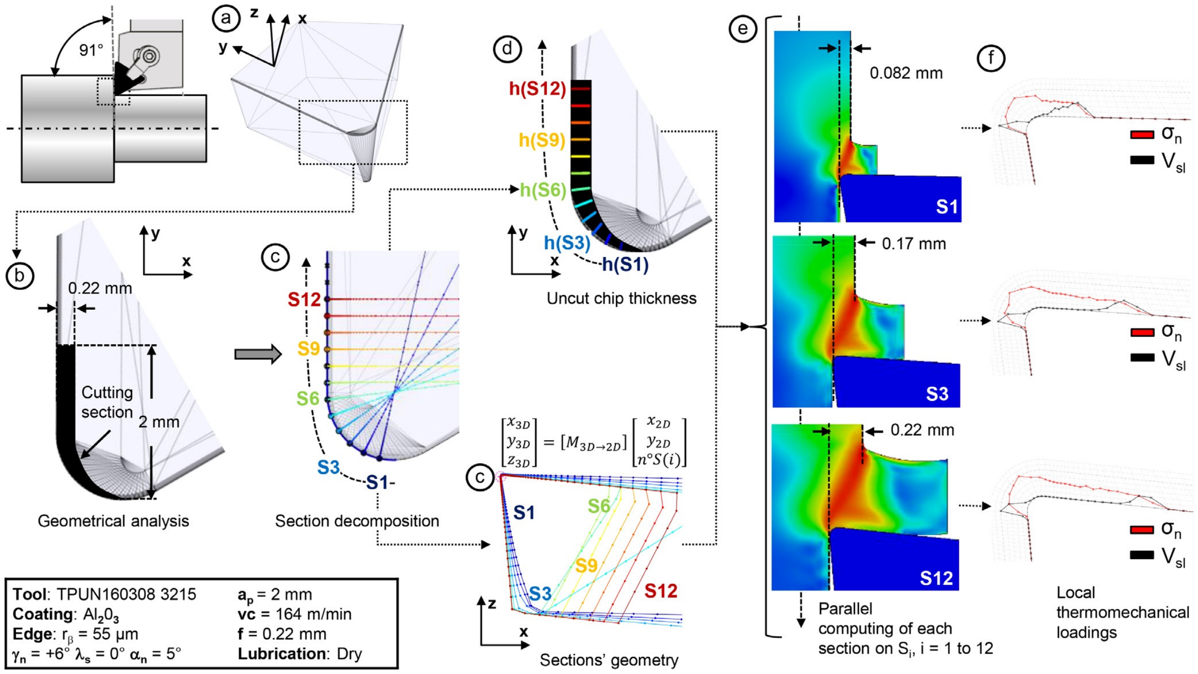


304L
H10F + TiN Cutting
Vc = 260 m/min
f = 0.1 mm/tr

Cutting duration : 306 sec
Simulation duration : 26 h



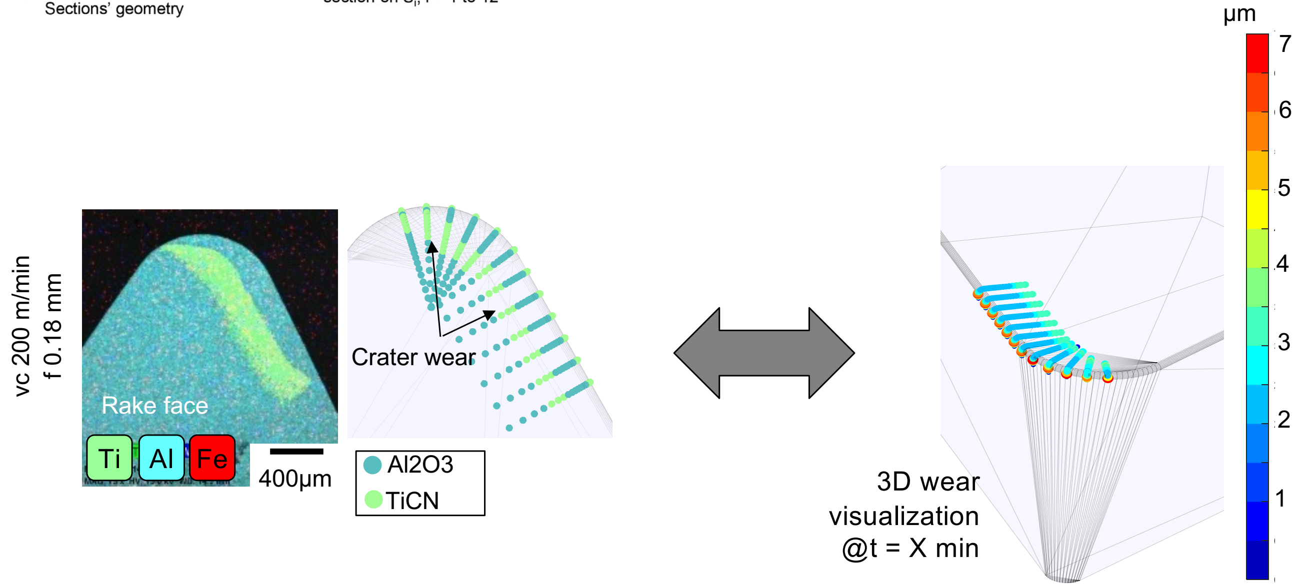
Usure des outils de coupe



Tool: TPUN160308 3215
Coating: Al_2O_3
Edge: r_β = 55 µm
γ_n = +6° λ_s = 0° α_n = 5°

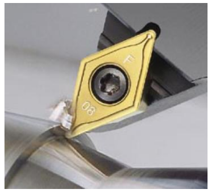
a_p = 2 mm
vc = 164 m/min
f = 0.22 mm
Lubrication: Dry

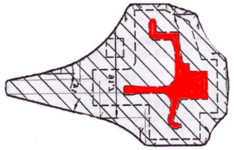
Modèles 2.5 D



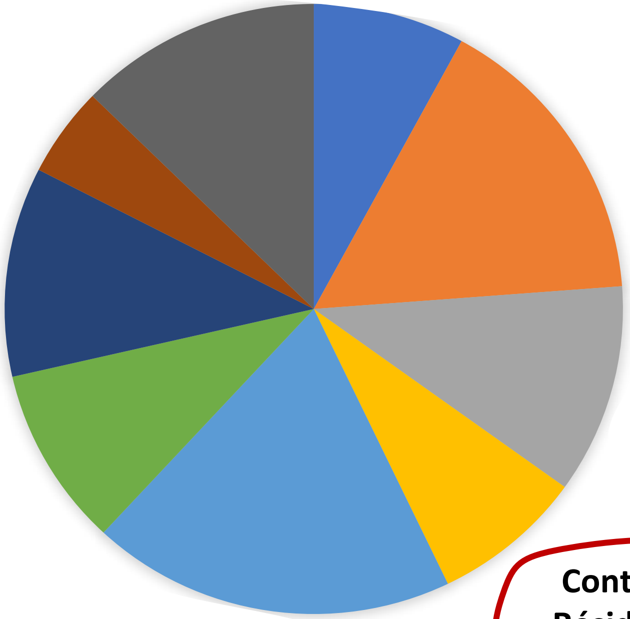
Les recherches académiques en usinage

Usinage Finition



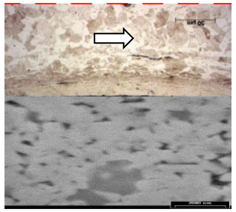


- ➔ **Contraintes résiduelles**
- ➔ **Microstructure**



Contraintes Résiduelles / Microstructure

Surfaces

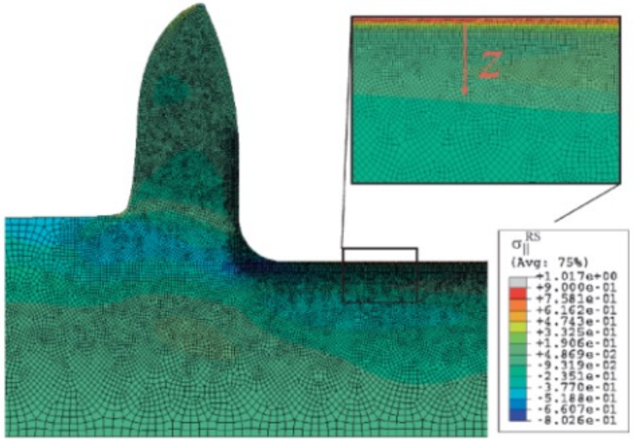


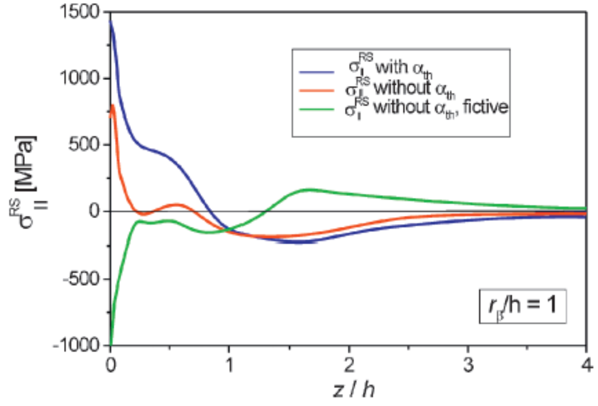
Modélisation des contraintes résiduelles

2 D

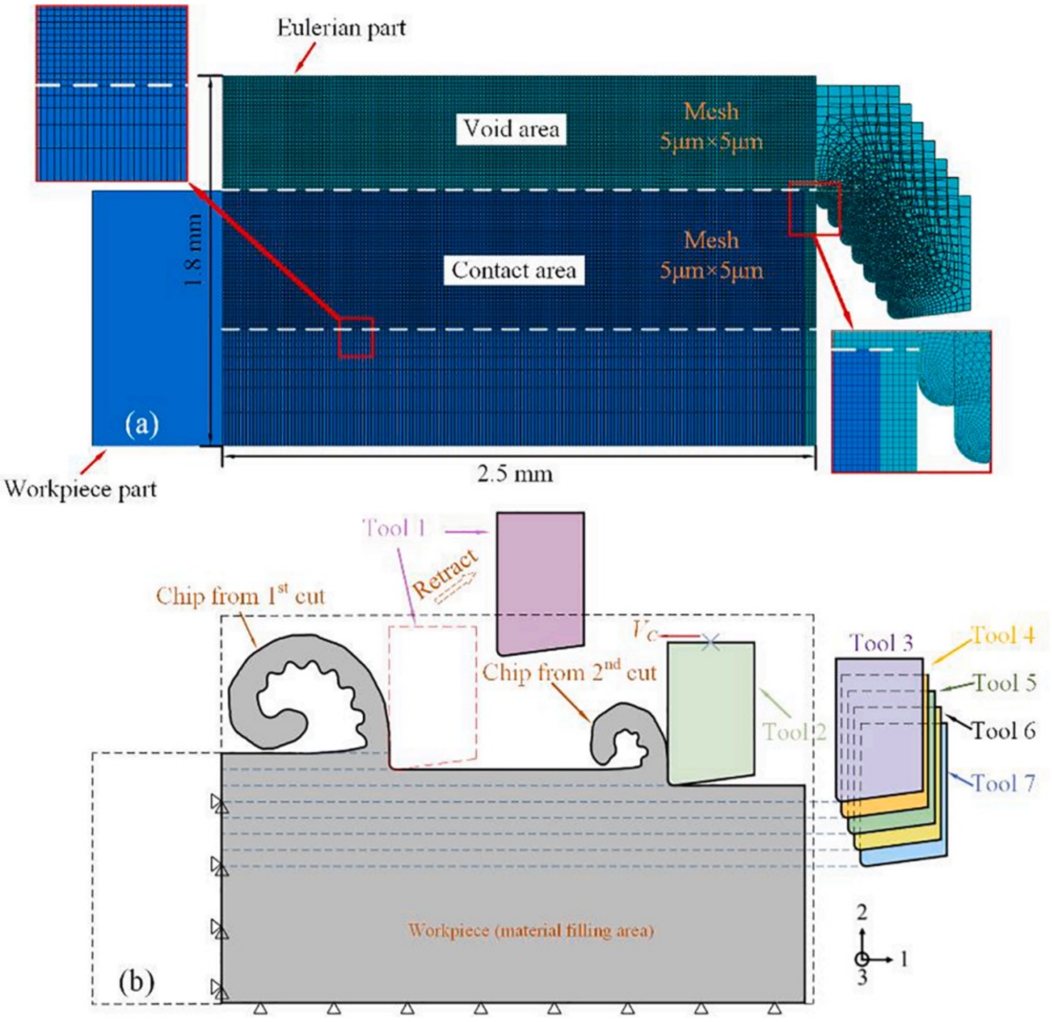
ALE / CEL

Explicit





Schulze et al. [2010]

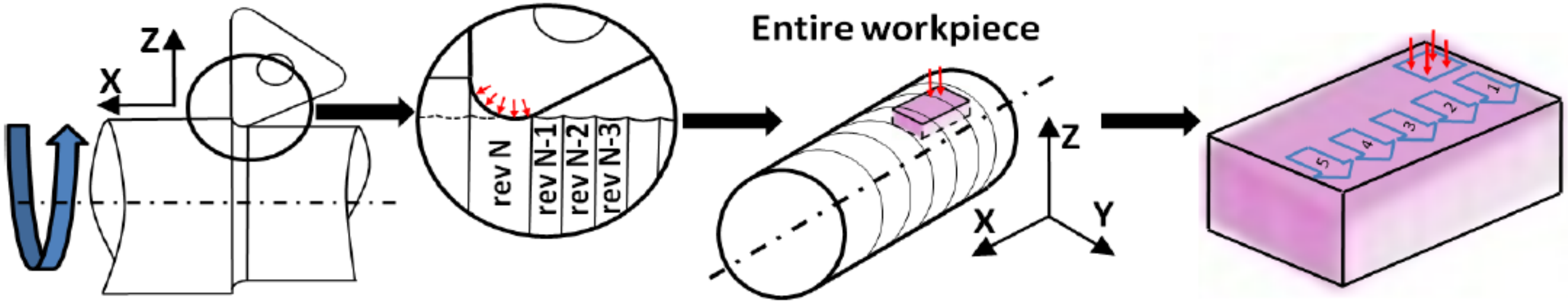


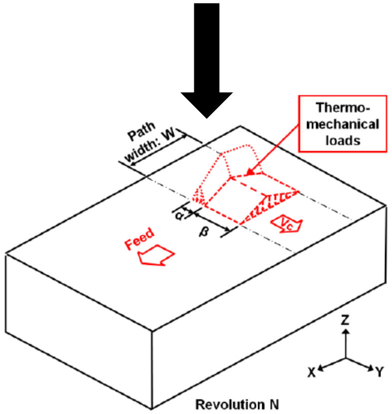
Zhuang et al. [2022]

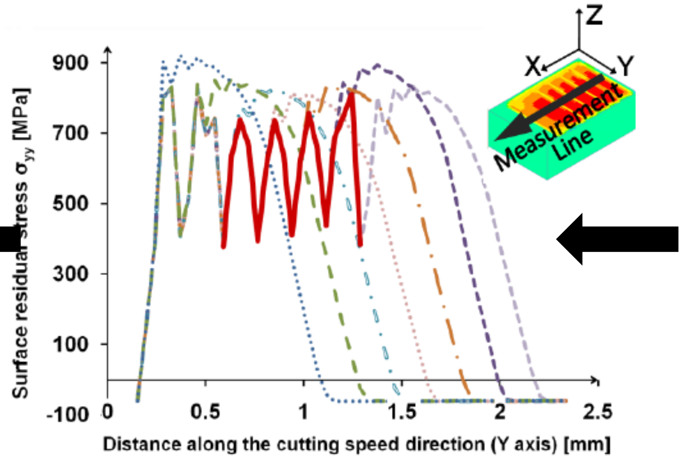
Modélisation des contraintes résiduelles

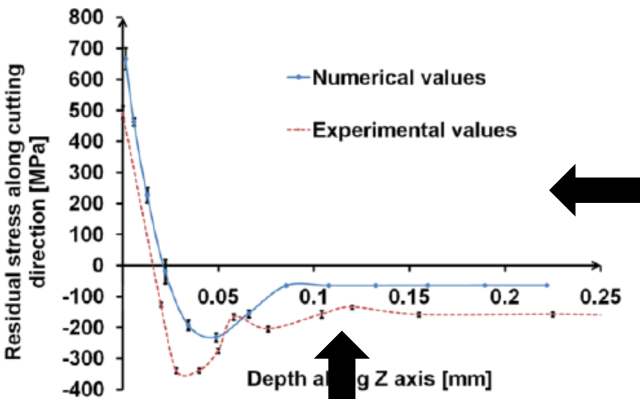
3 D

Hybride









X-Ray diffraction

SYSTUS
Implicit

MISULAB

Modélisation des contraintes résiduelles

MISULAB

Study #129 Process CREAPROF #3195

Revolution

Objects

- ☑ Part
- ☑ Profile
- ☐ Cut section
- ☐ Intersection points

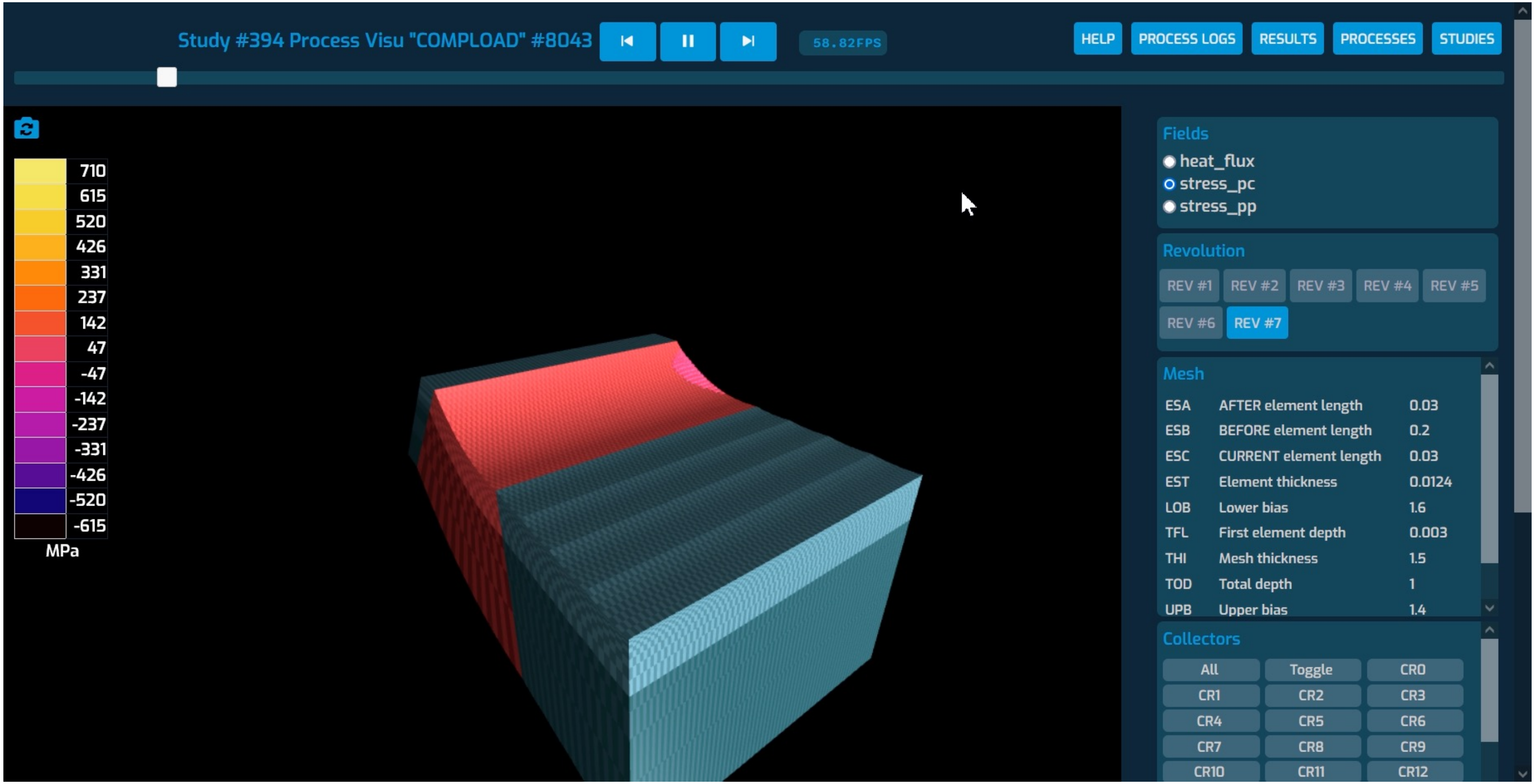
Tool

ANG	insert angle	55
ESR	edge sharpness radius	0.07
REP	insert tip radius	0.8
EDG	edge length	16

Trajectory

CURRAT	Current portion ratio	100
CUTDEP	Depth of cut (ap)	0.2
CUTSPE	Cutting speed	120
FINREV	Final revolution	8
INIREV	Initial revolution	1
KAPR	Tool lead angle (KAPR)	90
MACDIR	Turning direction	1
MAXREV	Max number of revolution	5

Modélisation des contraintes résiduelles



Study #394 Process Visu "COMPLOAD" #8043

Fields

○ heat_flux
● stress_pc
○ stress_pp

Revolution

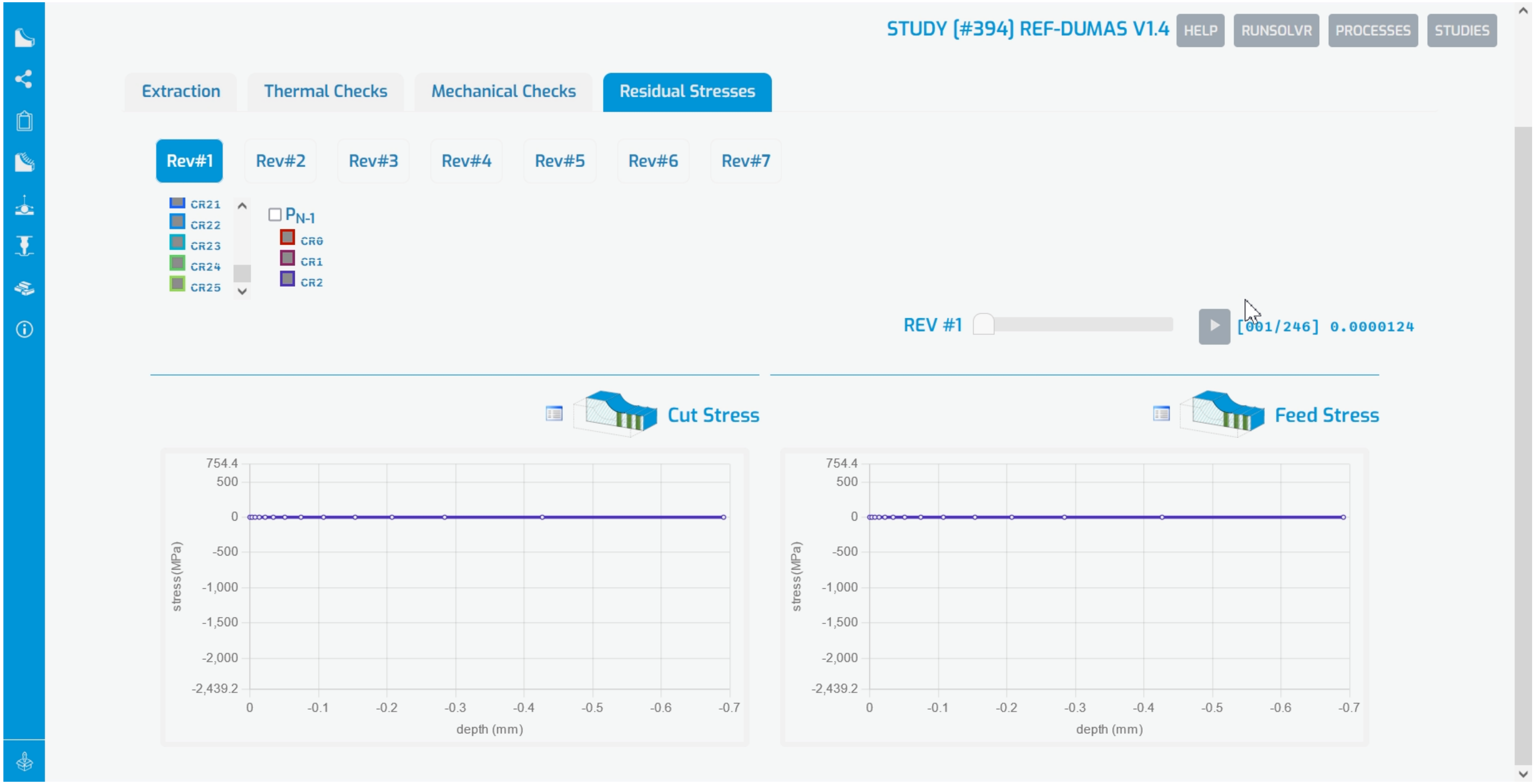
REV #1 REV #2 REV #3 REV #4 REV #5 REV #6 **REV #7**

Mesh

ESA	AFTER element length	0.03
ESB	BEFORE element length	0.2
ESC	CURRENT element length	0.03
EST	Element thickness	0.0124
LOB	Lower bias	1.6
TFL	First element depth	0.003
THI	Mesh thickness	1.5
TOD	Total depth	1
UPB	Upper bias	1.4

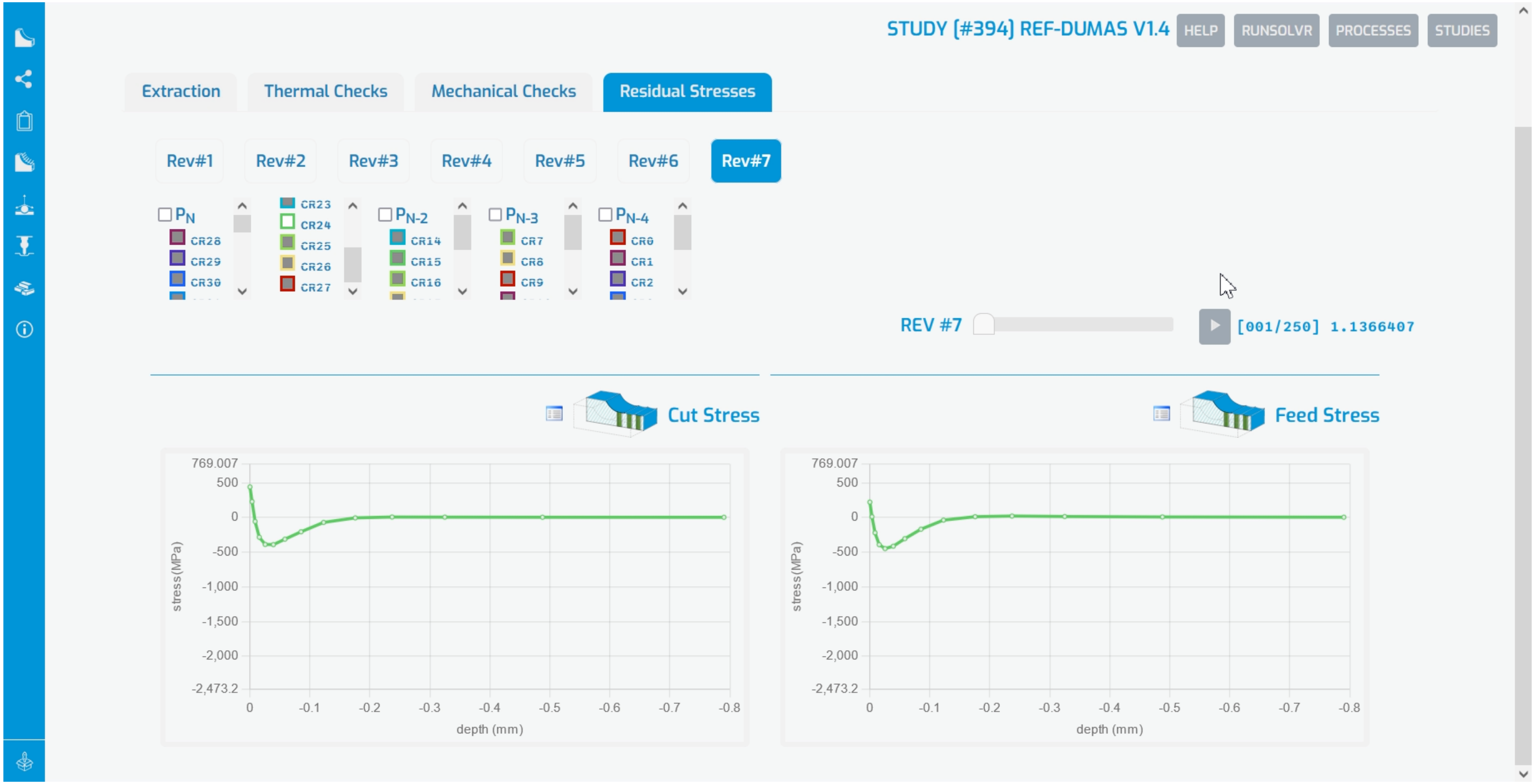
Collectors

Modélisation des contraintes résiduelles

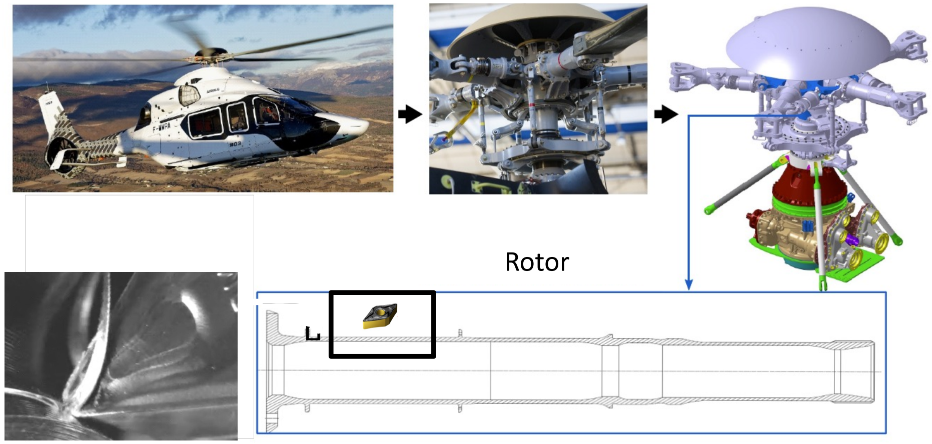


Modélisation des contraintes résiduelles

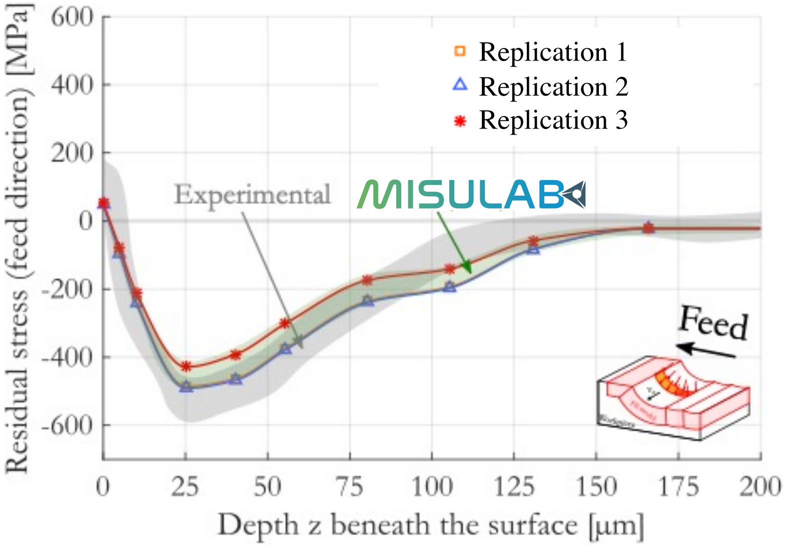
MISULAB

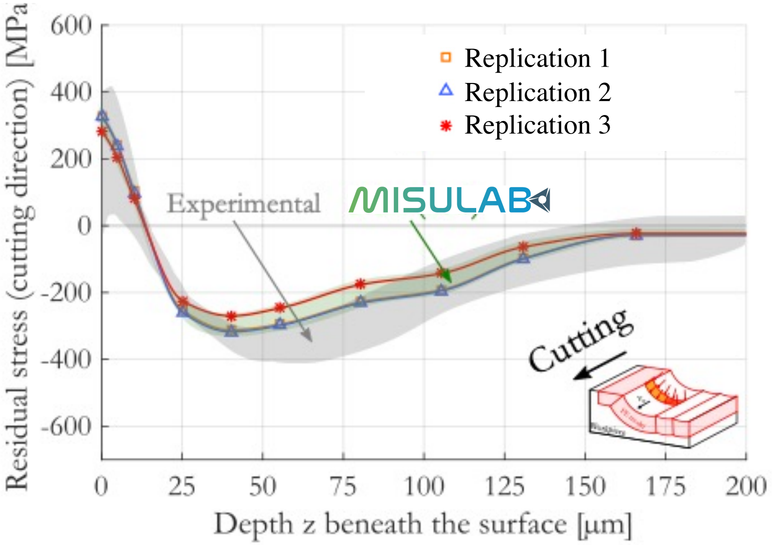


Modélisation des contraintes résiduelles



Material : 15-5PH
Insert : DNMG 150608
Cutting speed : Vc = 120 m/min
Feed : f = 0.2 mm/rev
Depth of cut : a_p = 0.2 mm
Cutting fluid : dry





Contexte

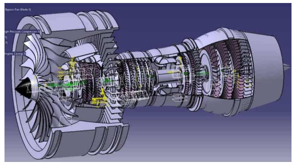
σ Contraintes résiduelles — MISULAB

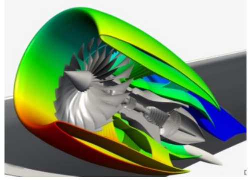
CONCEPTION
- DESSIN
- CALCUL

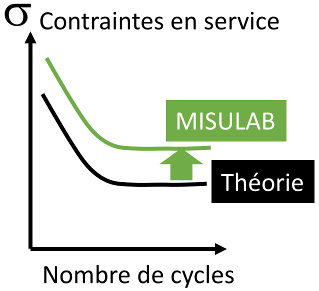
INDUSTRIALISATION (dont USINAGE)

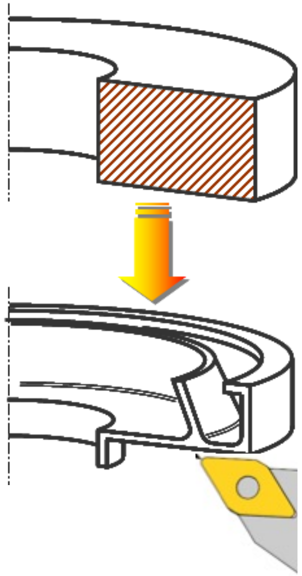
PROTOTYPE / DURABILITE

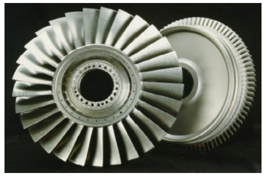
CERTIFICATION

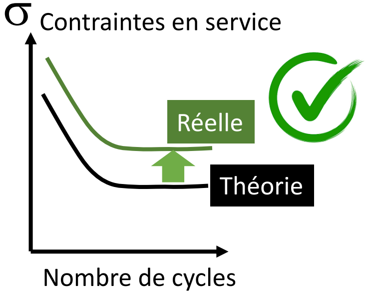










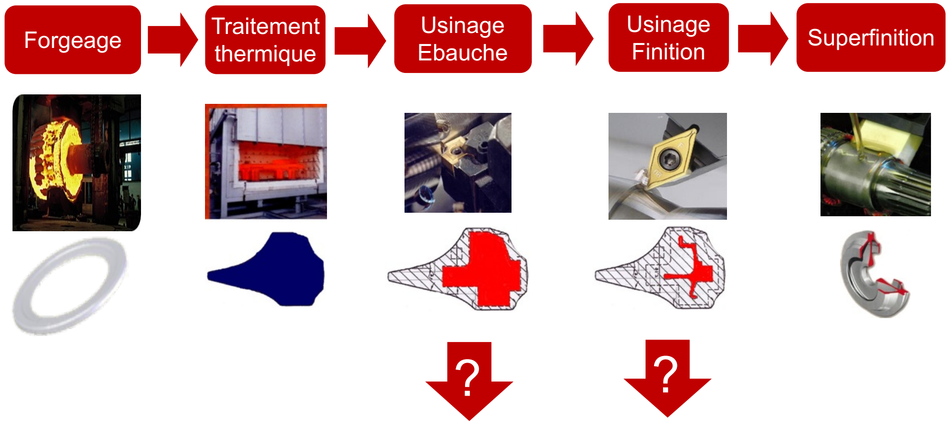


EASA
European Aviation Safety Agency

Résumé

Besoins industriels

- Prédire des indicateurs industriels
- Outils simples / rapides / ergonomiques
- Base de données d'entrée fiables et facile à alimenter
- Traçabilité et Pérennité
- Validation sur un large spectre de situations industrielles (montée en TRL)
- Prise en compte de la variabilité naturelle des conditions de production (usure outils, microstructure)
- Outils doivent s'interfacer dans une chaine numérique globale


Forgeage → Traitement thermique → Usinage Ebauche → Usinage Finition → Superfinition

Usinage Ebauche :
- ➔ Forces
- ➔ Géométrie
- ➔ Usure d'outils
- ➔ Fragmentation des copeaux

Usinage Finition :
- ➔ Forces
- ➔ Géométrie
- ➔ Rugosité
- ➔ Microstructure
- ➔ Contraintes résiduelles
- ➔ Usure d'outils
- ➔ Bavures
- ➔ Fragmentation des copeaux

Résumé

Besoins industriels

- Prédire des indicateurs industriels
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Modèles actuels

- Modèles 3D qui intègrent de nombreux phénomènes physiques et multi-échelles simultanément
- Modèles complexes à mettre en œuvre et qui restent à l'échelle de la preuve de concept (TRL 2-3)
- Temps de simulation trop importants (ms ⇔ jours)
- Importantes incertitudes sur les données d'entrée (Loi de comportement, tribologie, …)
- Modèles qui optimisent des grandeurs physiques locales (déformation, T°C,…)
- Enjeu de pérennité des modèles

Vers des simulations de l’usinage en industrie

Perspectives

- Temps de simulation de qq heures *(« loi des 80/20 ») :* ex. Modèles 2,5D, Réduction de modèles, …
- Prendre en compte la variabilité industrielle (ex. Modèles hybrides)
- Un modèle par échelle + interfaçage entre les échelles
- Méthodes d’identification simples + méthodes inverses
- Transfert vers l’industrie (ex. mode SaaS)
- Pérennisation des modèles (mutualiser un environnement de développement)
- Interfacer les logiciels de simulation de l’usinage avec les autres maillons de la chaine numérique (FAO, calcul de fatigue, …)

CENTRALELYON
ENISE

LTDS
Tribologie et
Dynamique
des Systèmes
UMR 5513

Simulation des Procédés d’Usinage – Besoins industriels & Verrous

Prof. Joël RECH