Mechanical MicroManufacturing

Some Topics

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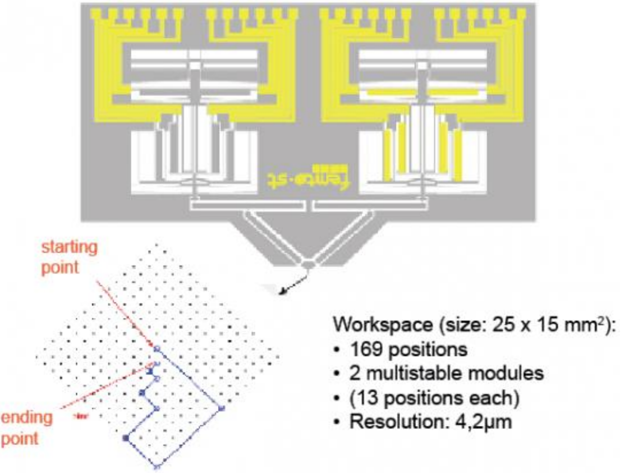
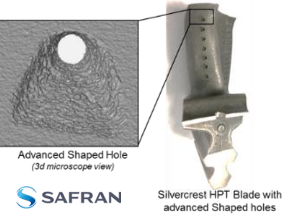
EPFL HIM Program – Doctoral Program

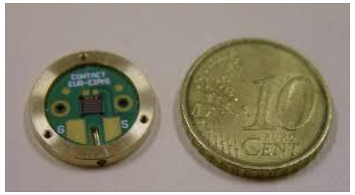
Overview

- Introduction
- Scale effects
- Under the millimeter scale : Micromanufacturing processes
- Micromachining
- Microforming

Introduction





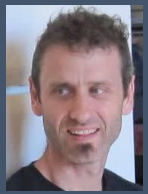


Intelligent MicroEngineering Group

Presentation

IMEG

Intelligent MicroEngineering Group – Experts knowledge

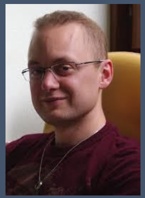


Gilles Bourbon
RI CNRS
Design
Micromanufacturing
MEMS
Actuators & Sensors

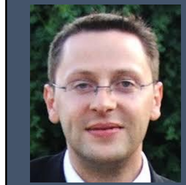
Patrice Le Moal
SR CNRS
Microsystems
Modeling
Multiphysics simulations

Xavier Gabrion
RE ENSMM
Experimental Mechanics
X-Ray Tomography

Julien Monnet
Teacher PhD
Design
Compliant systems
EDM



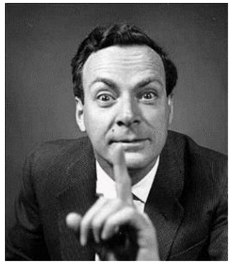
Emmanuel Ramasso
AP ENSMM (HDR)
Monitoring
Acoustic Emission
Learning / Signal Proc.



Sébastien Thibaud
FP ENSMM
Micromanufacturing
Modeling and Design
Metrology

Vincent Walter
AP UFC
Experiments
Microsystems
Dynamic Analysis

Introduction



Richard Feynman – There's plenty of room at the bottom – Caltech Engineering and Science, Vol 23:5, pp22-36 (1960)
Mark J. Jackson - Micro and Nano Manufacturing – 699p, Springer Edition (2007)

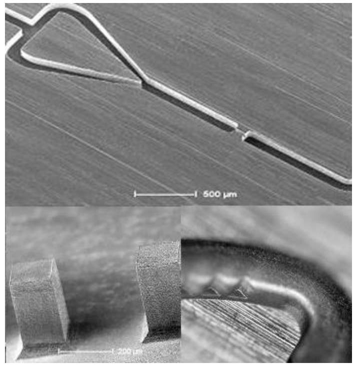
The book is written in the spirit of scientific endeavor outlined by ***Richard Feynman, who stated that one of the greatest challenges to scientists in the field of miniaturization is the manufacture of tiny objects using techniques as turning, molding, stamping and drilling***

nm

femto-st SCIENCES & TECHNOLOGIES

µm

MIFHySTO



mm

Mechanical Micromanufacturing

- Downsizing, Understanding and Controling mechanical micromanufacturing processes (maching, forming, molding, ...)
- ***Chain and hybridization of Clean room / Gray Room technologies***
- ***Additive manufacturing at microscale and coupling***
- Surface texturation and functionnalization
- ***Surface and volume metrology***
- ***3D microcomponents and microproducts (not 2D 1/2 shapes) in various materials***

Introduction

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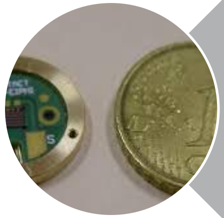
Develop and couple micromanufacturing techniques to produce (micro-)components with accurate geometries or submillimeter details (micro shapes)

Introduction

- Skills in Microtechnologies (Clean Room)
- Skills in Mechanical Micromanufacturing
- Skills in metrology and sensors development
- Skills in Machine Learning and signal processing

MIMENTO (Clean Room) + MIFHySTO
A unique ability near the micrometer scale to

- Chain microtechnologies and Mechanical MicroEngineering techniques
- Develop new intelligent micromanufacturing processes at micro-scale (part scale , shape scale, surface scale, …)
- Design and fabrication of microproducts
- Develop Modelling and design methods to chain microengineering techniques
- Develop metrology techniques to control and validate microproducts (surface, volume, defaults)
- Develop machine learning algorithms for enhanced monitoring of micromanufacturing process
- Real-world applications

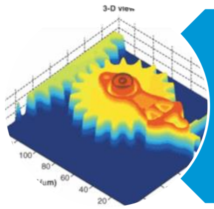


Microproducts

(MEMS, Micromechanics, Design, Modelling, Packaging, sensors)

Micromanufacturing

(Hybridization/Coupling, Intelligent MicroManufacturing, Gray & Clean Rooms)



Metrology at micro-scale

(Acoustic Emission, X-Ray Tomography, Surface and Geometrical control, vision, multiscale metrology)

Monitoring

(Signal Processing, Pattern recognition, Machine Learning, Deep Learning, System Identification)

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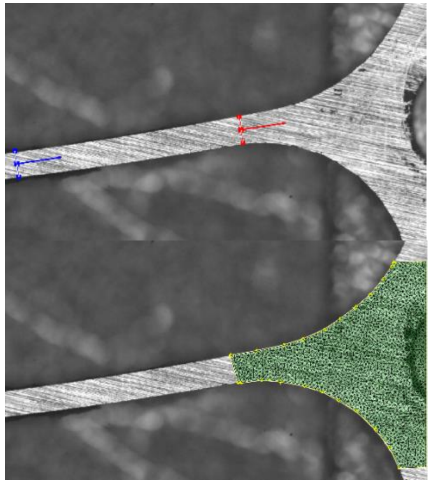
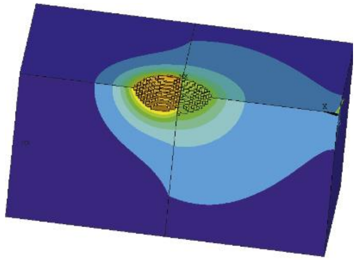
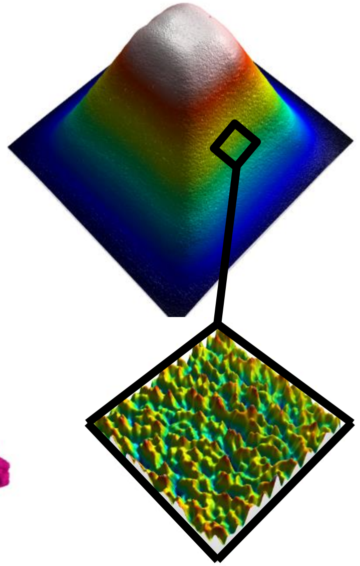
Introduction

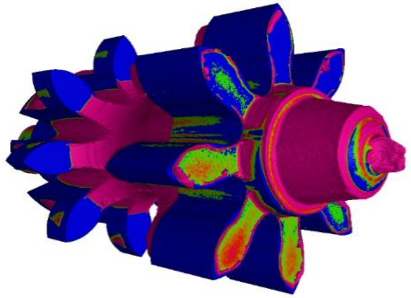
Hot topics in 2020

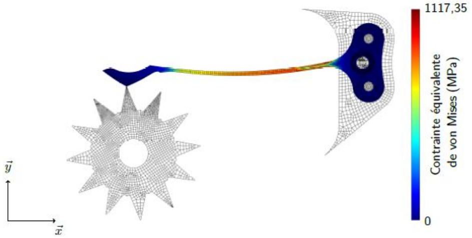
- Chain and hybridization of Clean room / Gray Room technologies
- Additive manufacturing at microscale and coupling (see Dr E. Boillat presentation)
- Surface and volume metrology
- 3D multifunctional microcomponents and microproducts (not 2D1/2 structures)
- Intelligent micromanufacturing

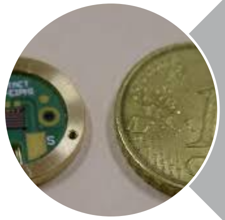










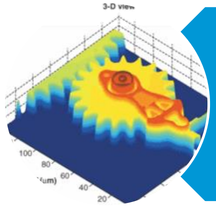


Microproducts

(MEMS, Micromechanics, Design, Modelling, Compliant mechanisms, Packaging, sensors)

Micromanufacturing

(Hybridization/Coupling, Intelligent MicroManufacturing, Gray & Clean Rooms)



Metrology at micro-scale

(Acoustic Emission, X-Ray Tomography, Surface and Geometrical control, vision, multiscale metrology)

Monitoring

(Signal Processing, Pattern recognition, Machine Learning, Deep Learning, System Identification)

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Objectifs

METROLOGY X-RAY TOMOGRAPHY
COMPLIANT SYSTEMS SIGNAL PROCESSING
COUPLING ACOUSTIC EMISSION MODELING
MONITORING MACHINE LEARNING
INTELLIGENT DEEP LEARNING GRAY ROOM
MICROPRODUCTS DESIGN SENSORS
CLEAN ROOM MULTIPHYSICS MULTISCALE
MICROMANUFACTURING MEMS

MICROENGINEERING

Objectifs

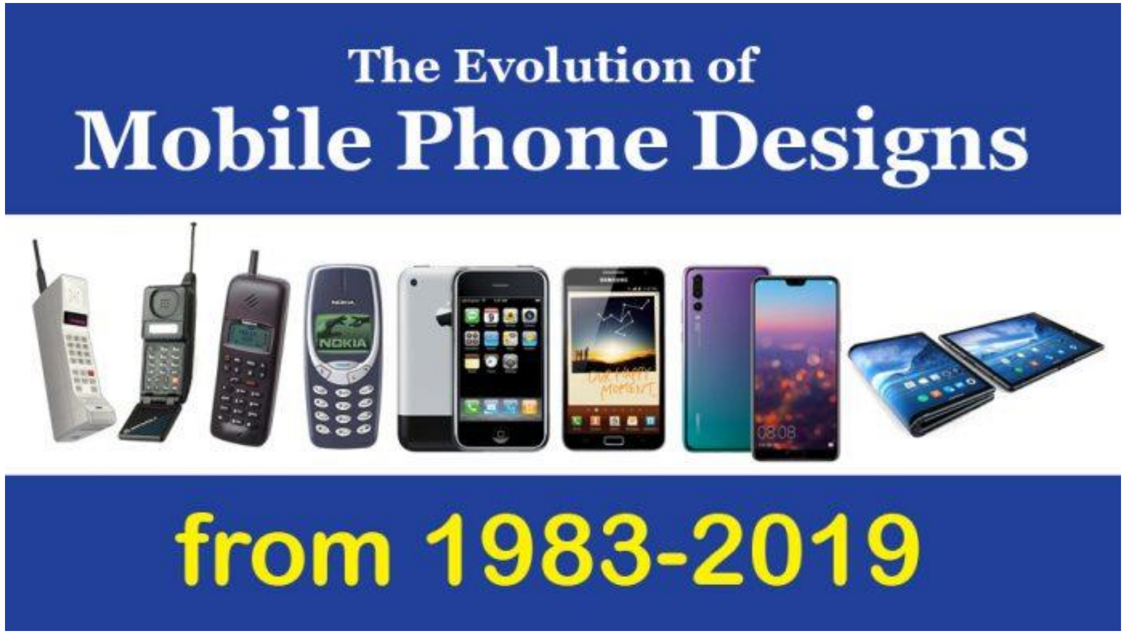
Micromanufacturing ?

First part : under millimetre scale

Microproducts : why ?

Microproducts are widely used owing to their :
- Compactness
- Low material requirement,
- Low power consumption,
- High sensitivity

Markets ?
- Medicine
- Telecommunications
- Electronics
- Consumer goods
- Defense
- Automotives
- Aeronautics/Aerospace



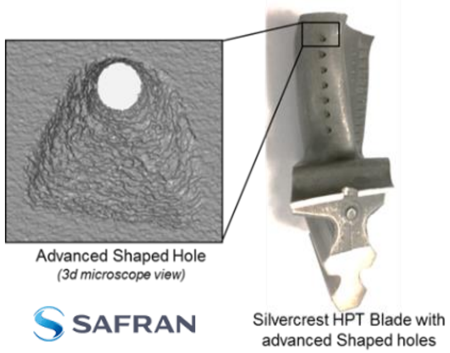
https://tallypress.com/fun/the-evolution-of-mobile-phone-designs-from-1983-2019/

Micromanufacturing is one of the fundamental technologies that lead the market of miniaturized products

Micromanufacturing : above the millimeter ?

Mechanical micromanufacturing processes are not only focussed on submillimeter parts

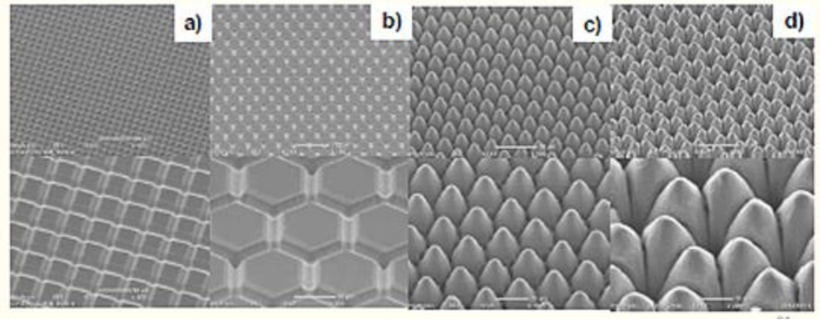
- Precision manufacturing : close tolerances (near the micrometer)
- Precise shapes : One of the dimensions is closed to the micrometer scale



Example : microholes (200 µm/ few mm length) in an advanced airblades in very hard material

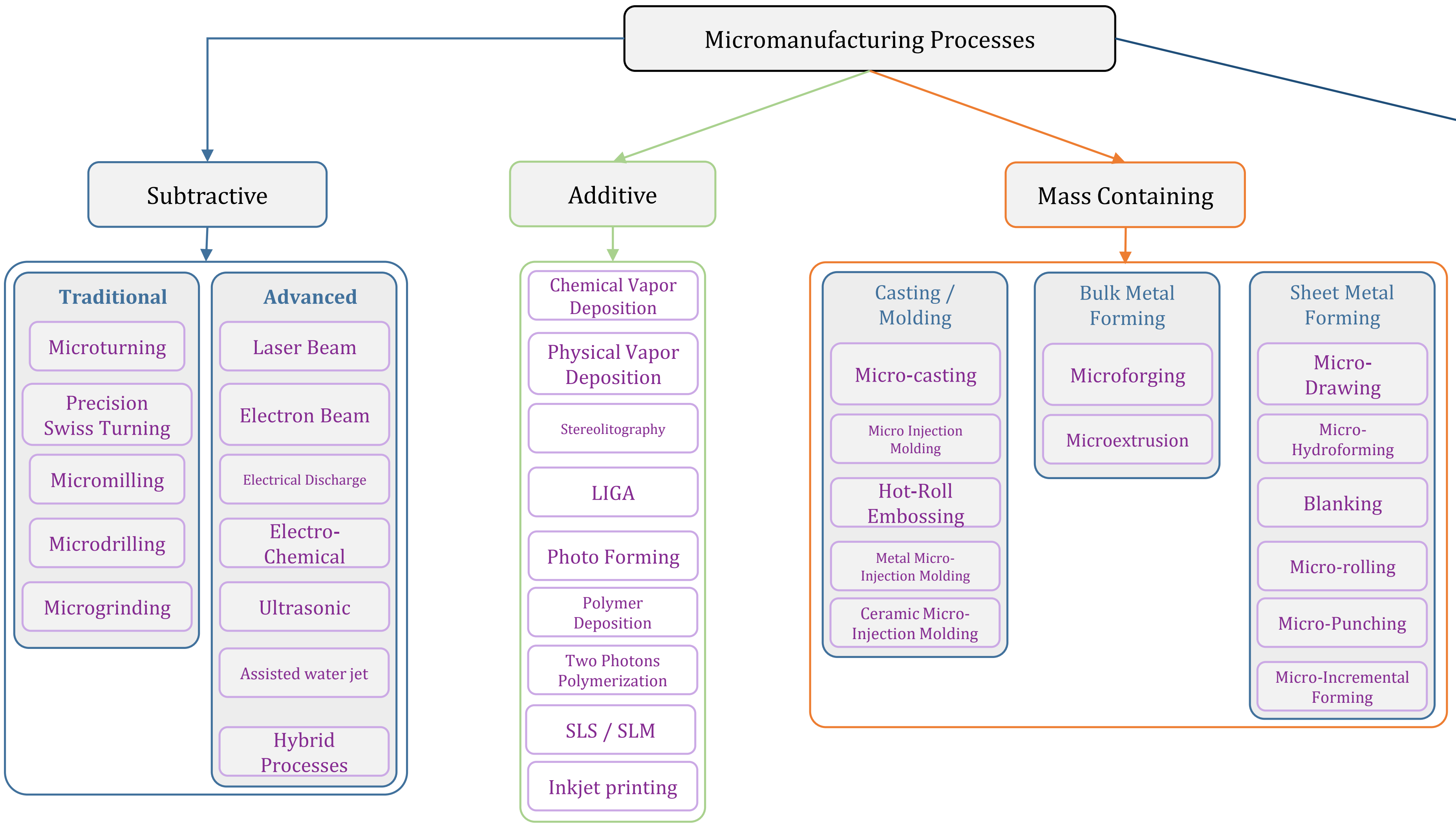
Micromanufacturing processes are also used to define surface properties on a component

Ex : fs laser surface texturing (see Pr. Y. Bellouard presentation)



Micromanufacturing classification (simplified version)

First Part : under millimeter



Micromanufacturing classification (simplified version)

First Part : under millimeter

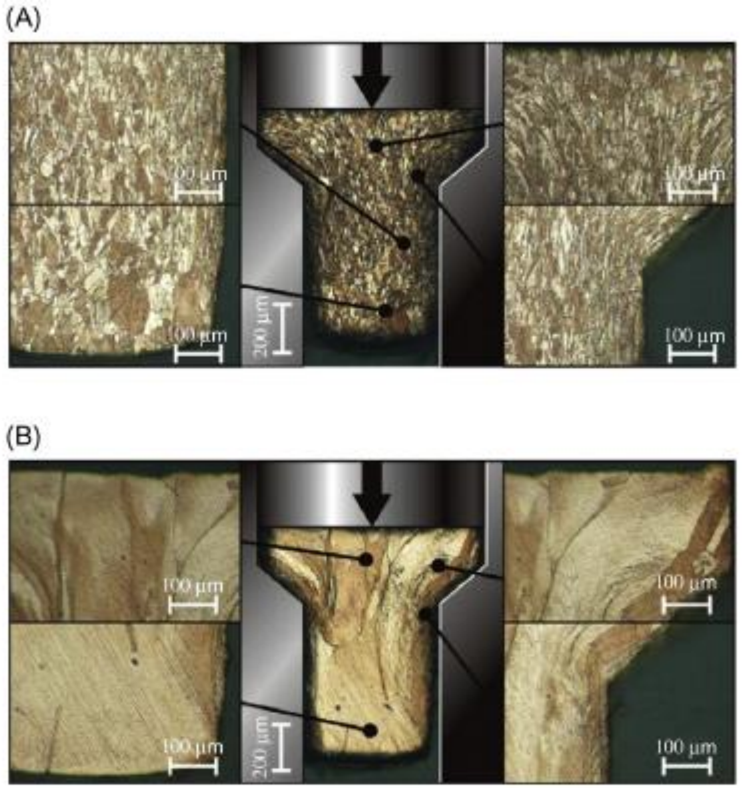
- Micromanufacturing Processes
  - Subtractive
    - **Traditional**
      - Microturning
      - Precision Swiss Turning
      - Micromilling
      - Microdrilling
      - Microgrinding
    - **Advanced**
      - Laser Beam
      - Electron Beam
      - Electrical Discharge
      - Electro-Chemical
      - Ultrasonic
      - Assisted water jet
      - Hybrid Processes
  - Mass Containing
    - Casting / Molding
      - Micro-casting
      - Micro Injection Molding
      - Hot-Roll Embossing
      - Metal Micro-Injection Molding
      - Ceramic Micro-Injection Molding
    - Bulk Metal Forming
      - Microforging
      - Microextrusion
    - Sheet Metal Forming
      - Micro-Drawing
      - Micro-Hydroforming
      - Blanking
      - Micro-rolling
      - Micro-Punching
      - Micro-Incremental Forming

In this lecture, we will focus on Subtractive and Mass Containing processes…

… and just a few

If we have enough time

- **Traditional**
  - Microturning
  - Precision Swiss Turning
  - Micromilling
- Bulk Metal Forming
  - Microforging
  - Microextrusion
- **Advanced**
  - Electrical Discharge
  - Ultrasonic
  - Laser beam assisted by water jet
  - Hybrid Processes
- Casting / Molding
  - Micro Injection Molding
  - MIM
- Sheet Metal Forming
  - Micro-Drawing
  - Blanking
  - Micro-rolling
  - Micro-Punching
  - Micro-Punching
  - Micro-Incremental Forming



W.L. Chan et al., Study of size effect in micro-extrusion process of pure copper, Materials and Design - 2011

Foreword : scale effects

An introduction

Scale effects

Manufacturing technologies can benefit from the relatively mature scientific background of conventionnal processes at macroscale

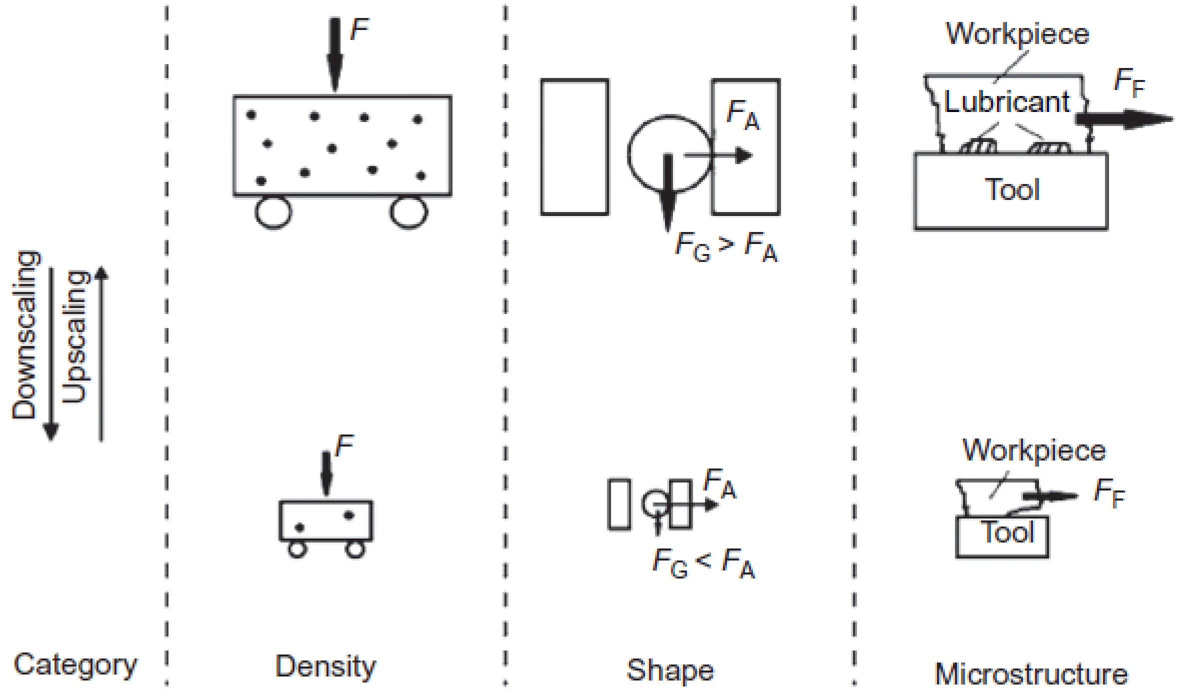
There is one issue that micromanufacturing cannot mechanically copy from classical manufacturing : the so-called size effects

Size effects are deviations from intensive or proportional extrapolated extensive values of a prcess which occur, when scaling the geometrical dimensions (Vollertsen, Production Engineering, 2008)

This definition is applicable to a wide range of processes, as it not only predicts the influence that size effects could cause, but also takes the possibility that the dimensions of a wider range items (forces, speciment, tools) could change into consideration

Scale effects

Size effects are known as unique characteristics with miniaturization and can be categorised into 3 parts (Vollertsen)



Scale Effect Type 1 : Density size effects

- DSE normally occur when absolute value or internal value of typical quantity per volume (per density) is a constant and independent on the size of an object
- If the shape of an object is unchaged while its size does, the value of interest can change
- DSE are resulted due to decrease of the density of defects with decreasing the target size (small pores, dislocations lines or grain boundary

Scale effects

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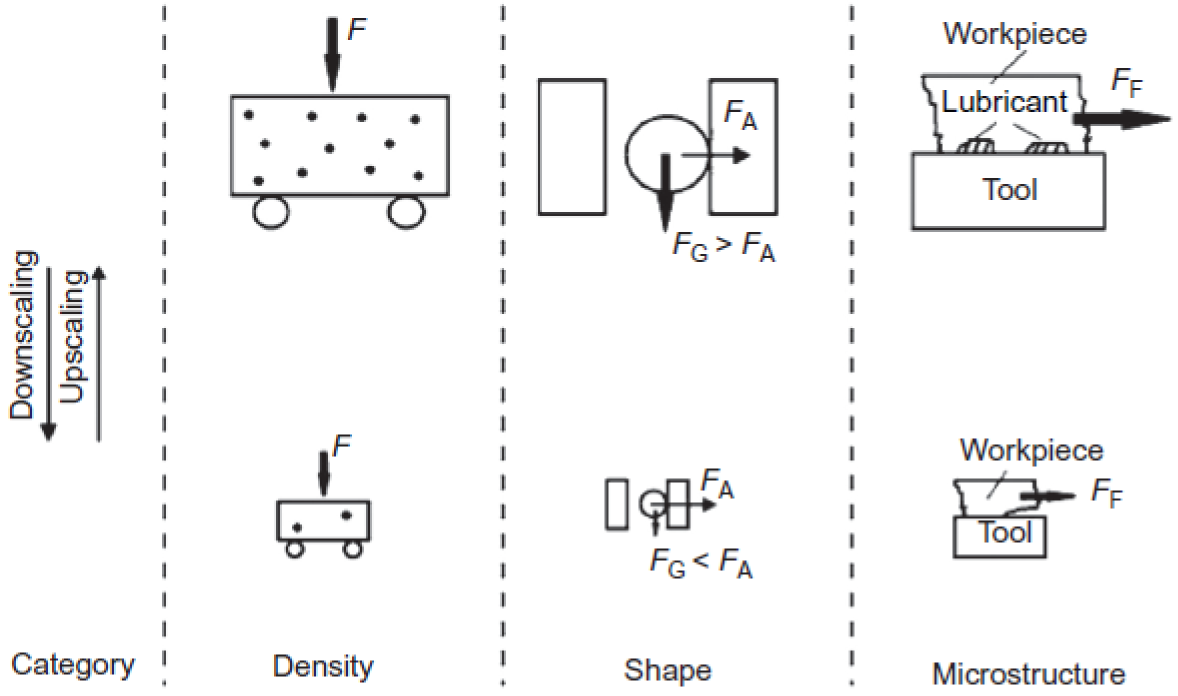
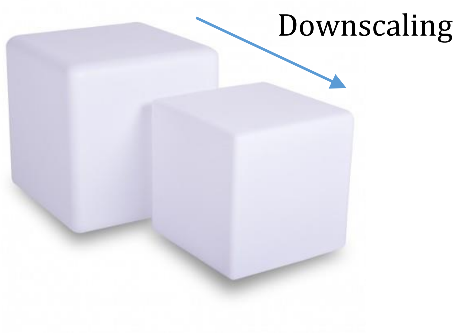


Scale Effect Type 2 : Shape size effects

- SSE are caused due to the change of relative dimensions among line, area and volume
- With the decrease of the target size, the ratios of the surface area and volume to the sample size decrease
- At microscale, surface effect are stronger than the volume effects



$$\frac{A}{V} \sim \frac{1}{l}$$

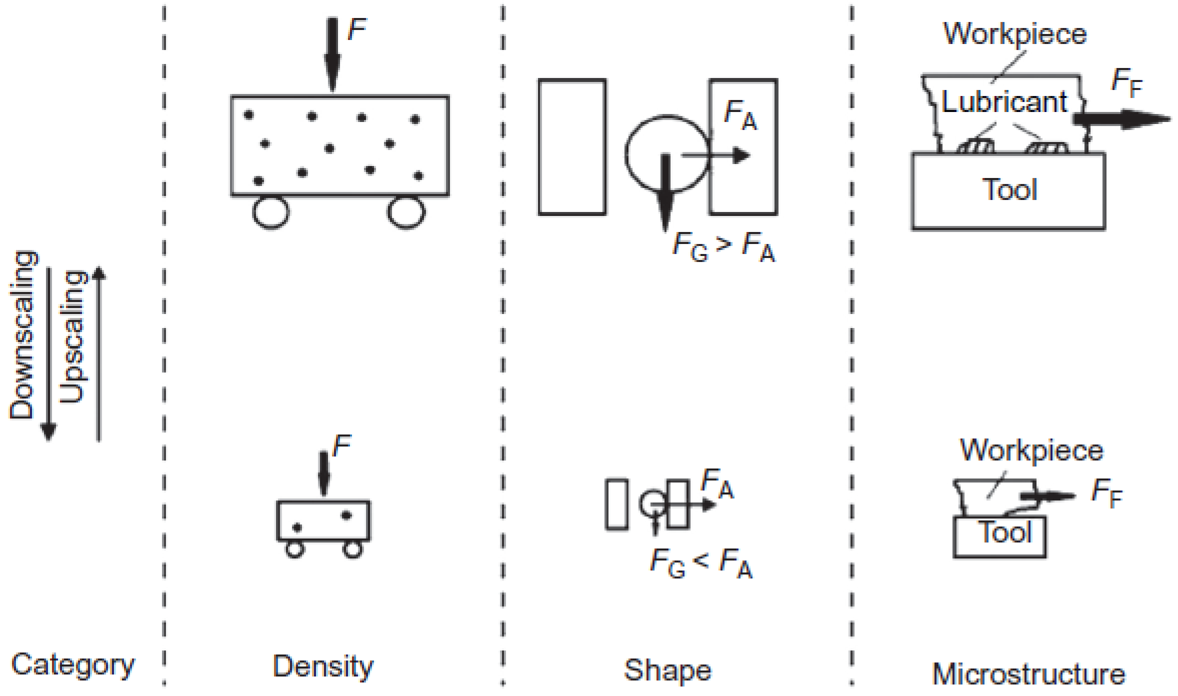
l ↗ V effects ↗

l ↘ A effects ↗

Introduction of a scaling law

Scale effects

Size effects are known as unique characteristics with miniaturization and can be categorised into 3 parts (Vollertsen)



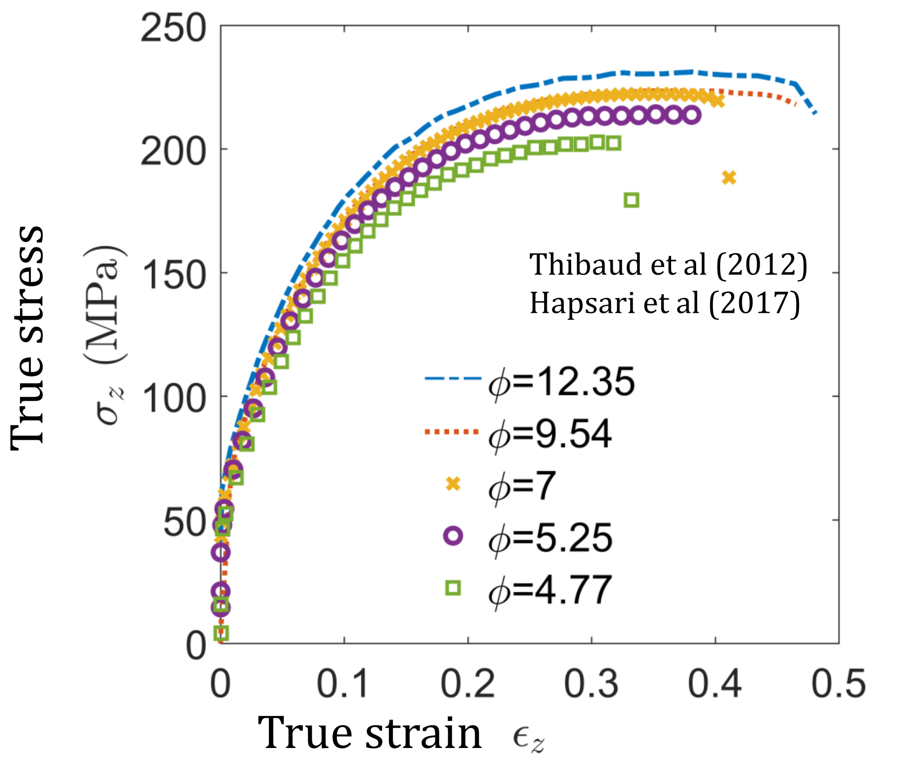
Scale Effect Type 3 : Microstructure Scale Effect

- Microstructural features are not scale down when the object size decreases
- Objects size remains while the characters of microstructure (grain size) experience changes
- In micromanufacturing, tribological conditions between the tool and workpiece are of great importance
- Tribological size effects become increasingly significant when process is scaled down (surface effects)

Scale effects

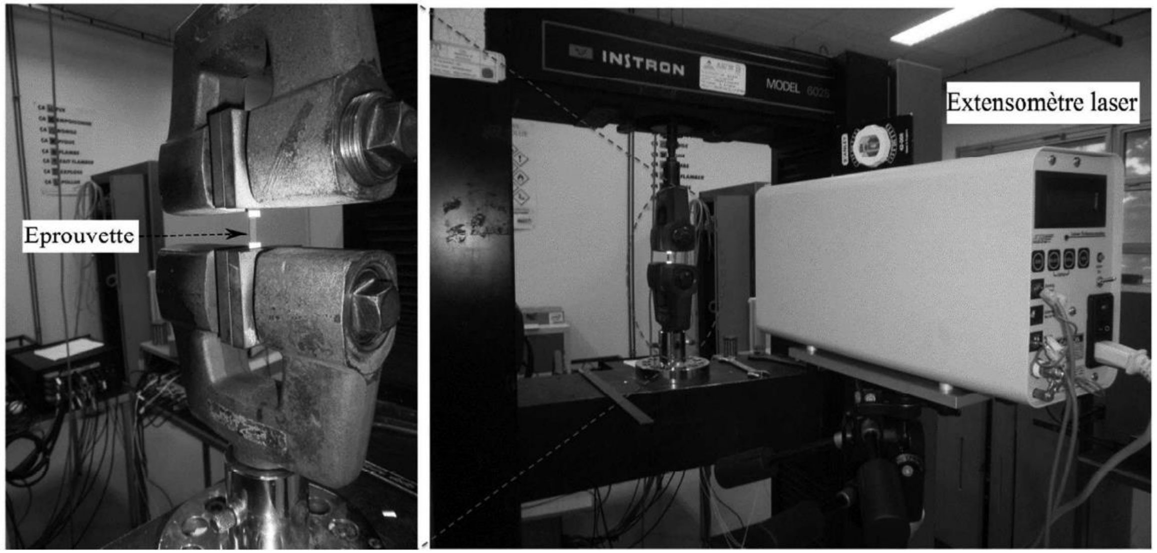
Problems associated to size effects

Size effects on mechanical behavior



Φ = thickness/grain size = number of grain in thickness

Tensile test on a copper alloy (thickness : 210 µm)



Influence of the initial grain size : Hall and Petch effects

$$\sigma_z \sim \frac{\sigma_y}{\sqrt{d}}$$

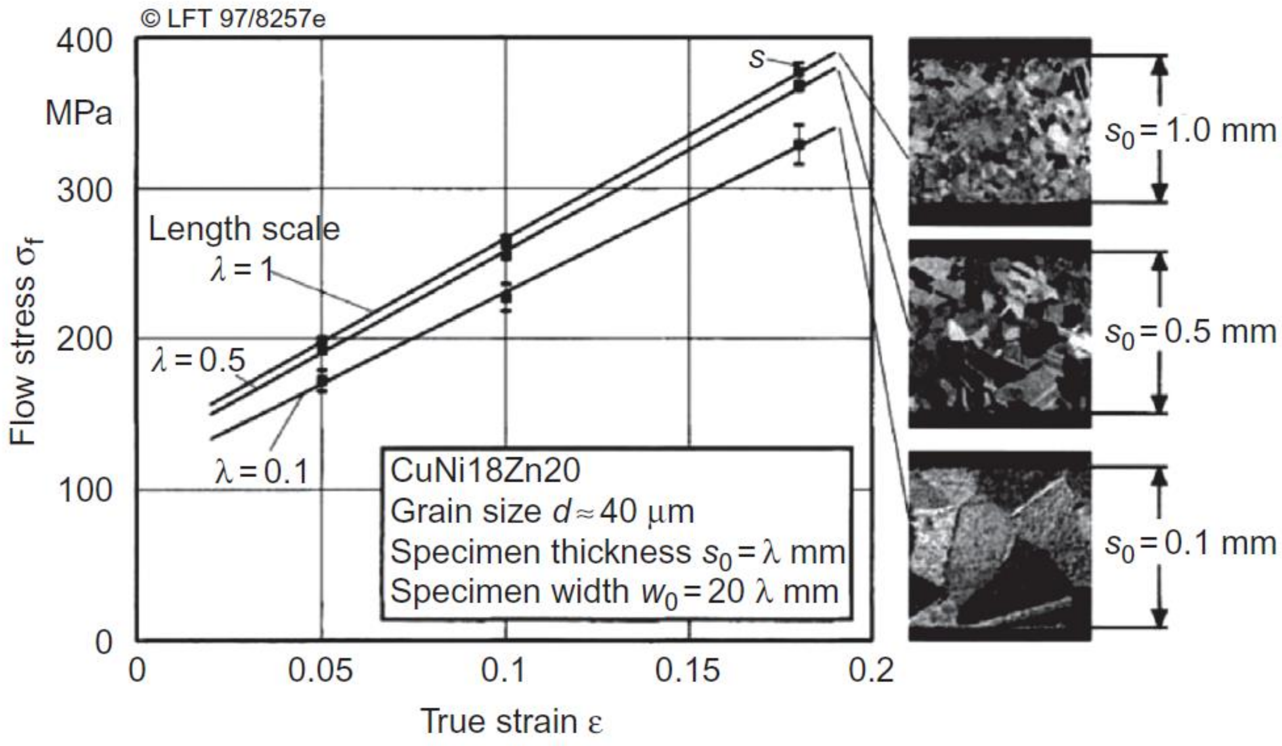
σ_y: yield stress (MPa)

d : initial grain size

d ⬂ σ_z ⬀

Problems associated to size effects

Size effects on mechanical behavior



Flow curves of CuNi18Zn20 for different values of the length scale. Kals and Eckstein, 2000

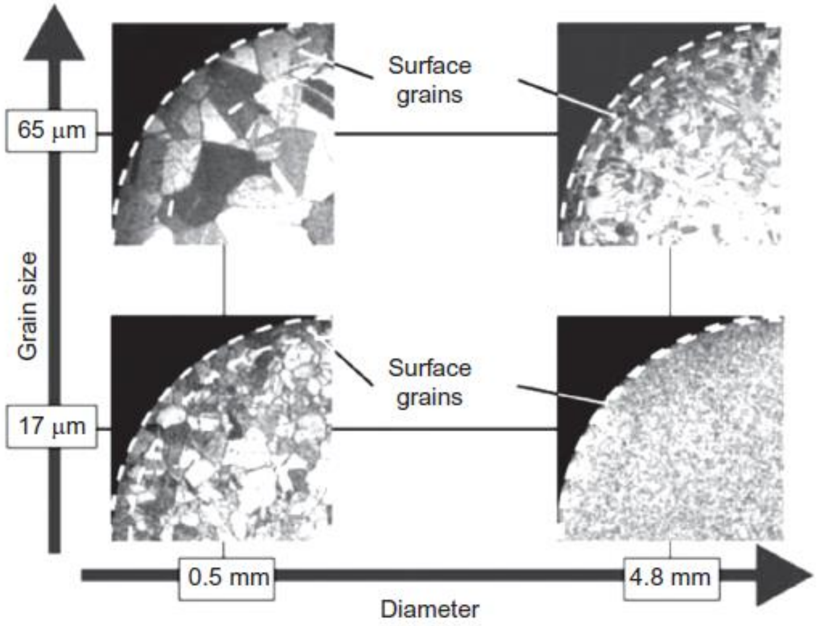
Same observation : Hall and Petch law

Problems associated to size effects

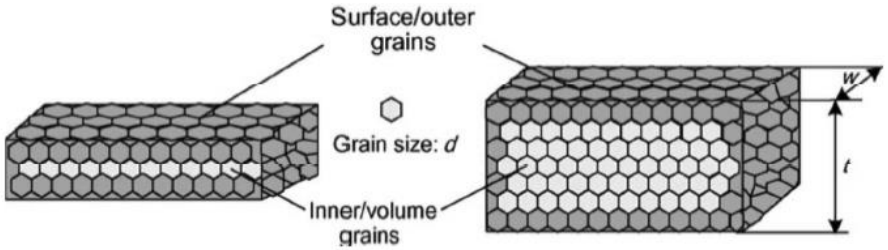
Size effects on mechanical behavior

Flow stress decreases with miniaturization when the grain size of speciment is held constantly

The decrease of flow stress is definitely caused by miniaturization instead of diffrent grain microstructures



Surface Layer model



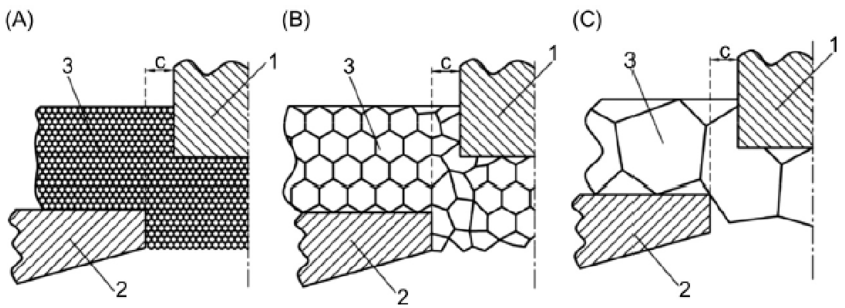
Kals et al., 1996 : The grains located on the surface show less hardening and cause low flow stress in metal foil
The moving dislocations pile up at grain boudary, but cannot pile up in the surface grains during deformations

Scale effects

Problems associated to size effects

Size effects on mechanical behaviorin blanking process

Influence of blanking clearance (C) to grain size (d) is one of the main factors affecting micro deformation behavior in microblanking



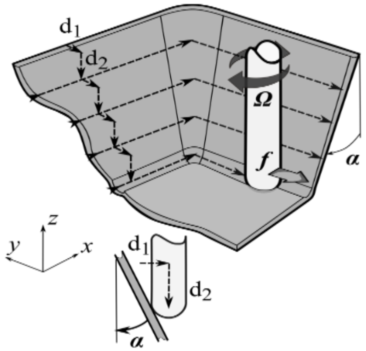
Xu et al, 2012

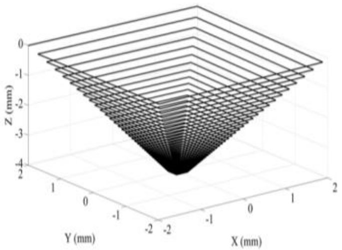
Scale effects

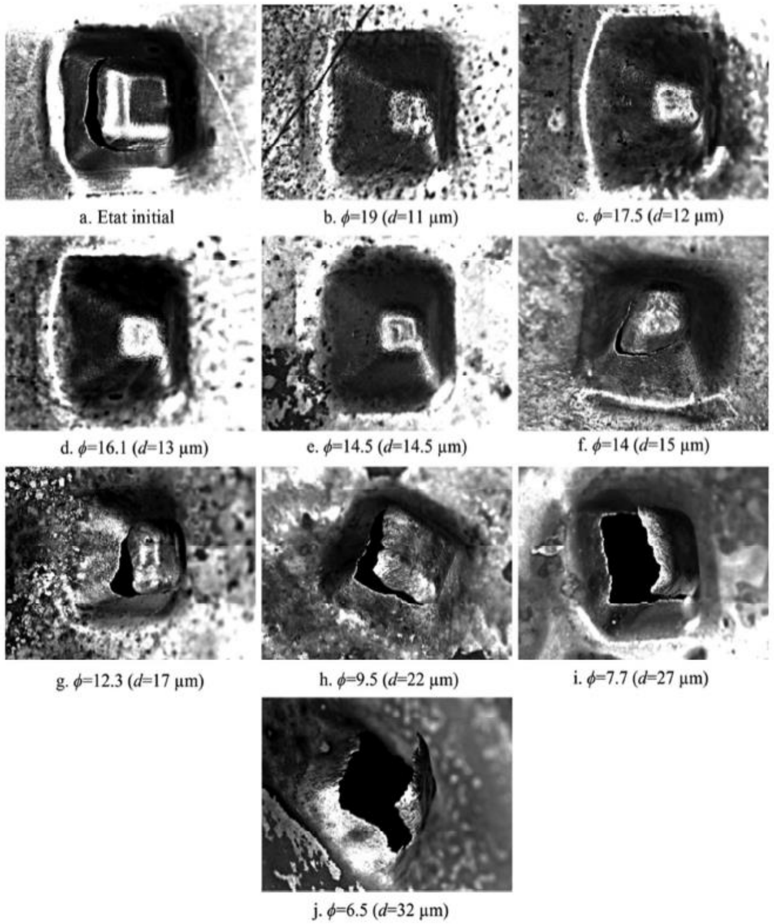
Problems associated to size effects

Size effects on mechanical behavior in micro-incremental forming

Influence of initial grain size on forming defects







Ben Hmida, S. Thibaud, F. Richard, 2012

Scale effects

Problems associated to size effects

Tribological size effects

In micromanufacturing, tribology has a significant effect on the quality of the produced part, tool lifetime and process stability (repeatability)

The tribological behavior depends on several parameters :

- Contact state between the material and tools
- Contact pressure
- Lubricant condition
- Surface topography (anisotropy, profile, …)

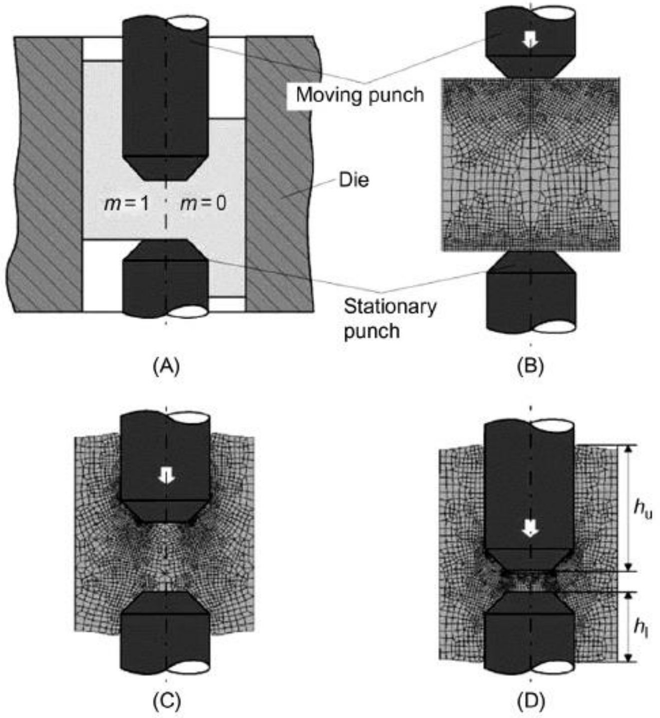
Contact area has a major influence on the frictional conditions

Scale effects

Problems associated to size effects

Tribological size effects

Double cup extrusion test (Engel and Eckstein, 2002)



Theoritical case of no friction (m=0) : h_u=h_l

$\frac{h_u}{h_l}$ ratio is quite a sensitive measure for friction

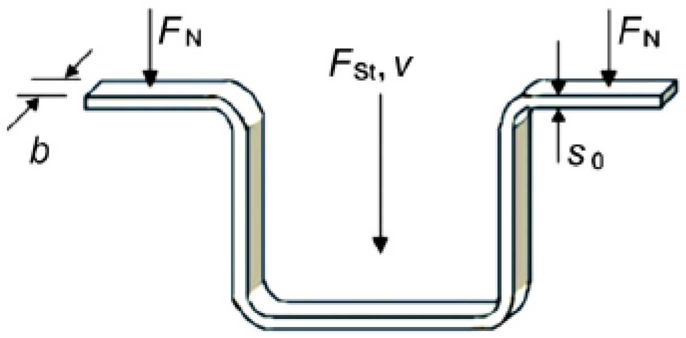
Friction increases distinctly with miniaturization

Scale effects

Problems associated to size effects

Tribological size effects

Strip drawing friction test



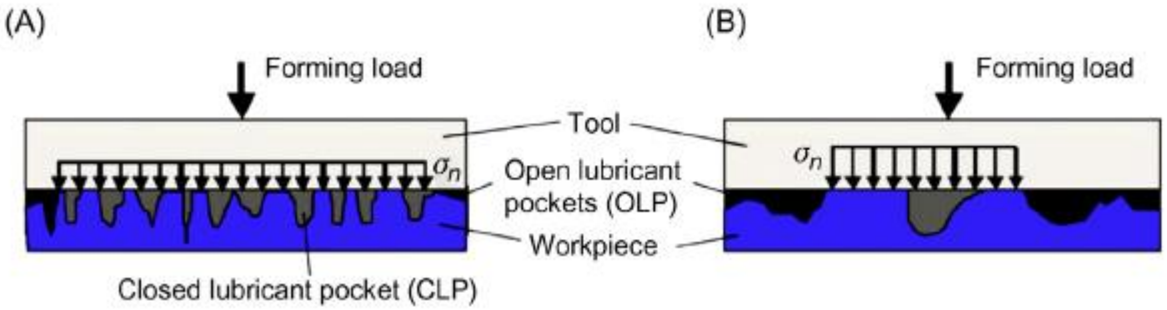
In micro-sheet forming, processes are sensitive to friction

In the test, a strip with a width *b* and thickness s_0 , under the blanholder force F_n , is drawn by a pungh with a velocity *v* into the die

By measuring, the punch force F_s it's possible to identify friction (Vollertsen)

Problems associated to size effects

Tribological size effects : lubricant friction behavior



Size effects on lubricant friction behavior can be explained by the model of open/clodes lubricant pockets or dynamic/static lubricant pockets

When a forming load is applied to a lubricated workpiece surface, the asperities start to deform plastically, and the pressure of the lubricant increases

Roughness valleys = connection of the edge of the surface and it cannot keep the lubricant (open lubricant pockets) – **Higher normal pressure**

Close lubricant pockets : no connection to the edge of the surface = creation of a hydrostatic pressure **reducing the normal pressure** which results in **lower friction**

OLP = friction ⬀ CLP = friction ⬂

Scale effects

Summary

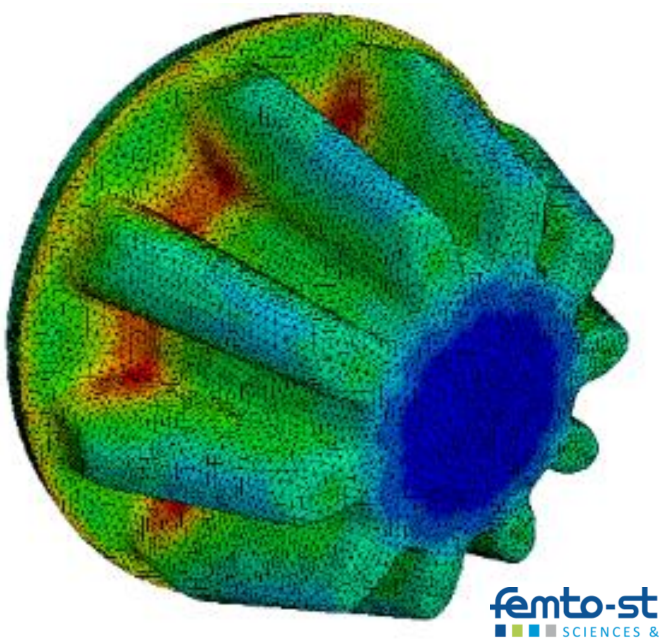
Size effects are critical at microscale

The miniaturization of processes does not consist of a simple downscaling of all parameters

Some scale effects can have positive effects : examples in nano-micro-robotics (see Pr Lutz's presentation)

In micromanufacturing, scale effects are often harmful and need to be controlled

During this presentation, scale effects will be regularly identified and presented



Net Shape Microforging - S. Thibaud – 2015

Microforming

Plastic deformation processes at micro-scale

A definition

Microforming is a set of processes based on the miniaturization of **metal forming processes**

Bulk Metal Forming
- Microforging
- Microextrusion

Sheet Metal Forming
- Micro-Drawing
- Blanking
- Micro-rolling
- Micro-Punching
- Micro-Punching
- Micro-Incremental Forming

Microforming can be defined as the process of manufacturing a part or a feature by **plastic deformation**, whose at least one orthogonal view can be enclosed in a square of 1mm size

Dixit US and Das R. CRC Press, 2012

Microforming is also defed as the production of parts or structures with at least two dimensions in the submillimeter range by using mechanically based processing technology

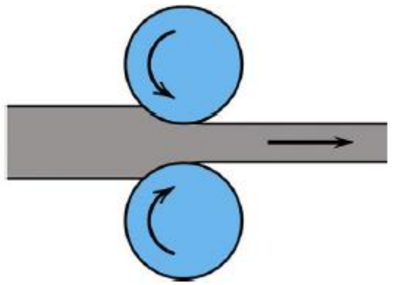
Geiger, Kleiner and Eckstein, 2001

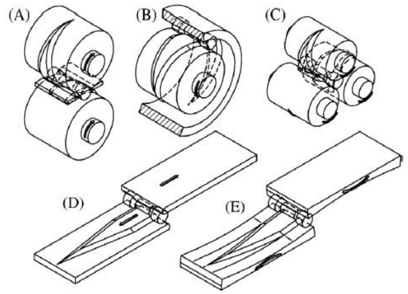
Parts obtained by microforging (Vollertsen, 2004)

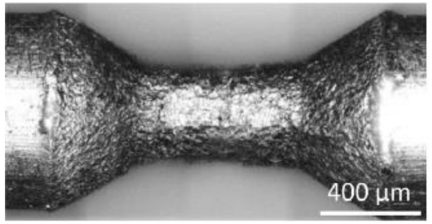
From the viewpoint of production engineering, microforming is considered as an effective process to economically and precisely manufacture micro-products (in case of bulk production)

Some example

Micro-rolling



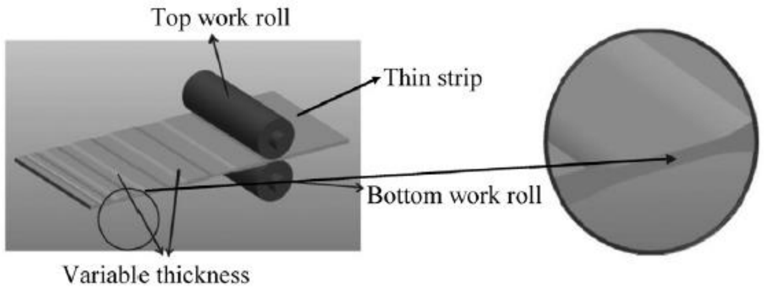




In metalforming, rolling is an essential processes in which workpiece is passed trough one or more pairs of rolls (or special rolls) to reduce the thickness (sheet or foils) or to form particular shaped products

Micro-rolling is the common process to obtain very thin sheets (up to few microns) used in other microforming processes.

Material hardening behavior is a key factor in micro-rolling in relation with associated scale factors (grain size, anisotropy, quality surface of the tools, friction, …)



Some example

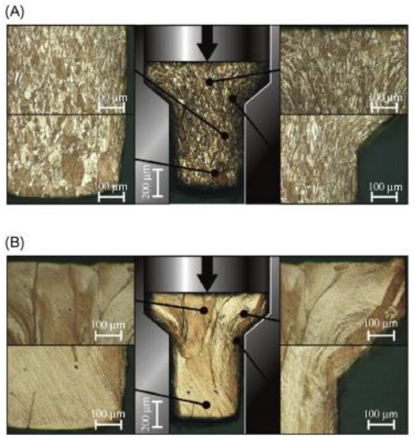
Micro-extrusion

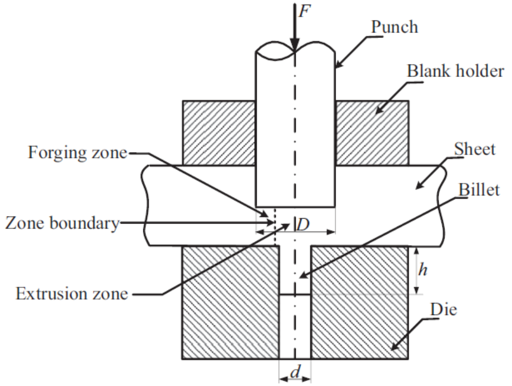
Micro-extrusion is classified either as forward or backward extrusion

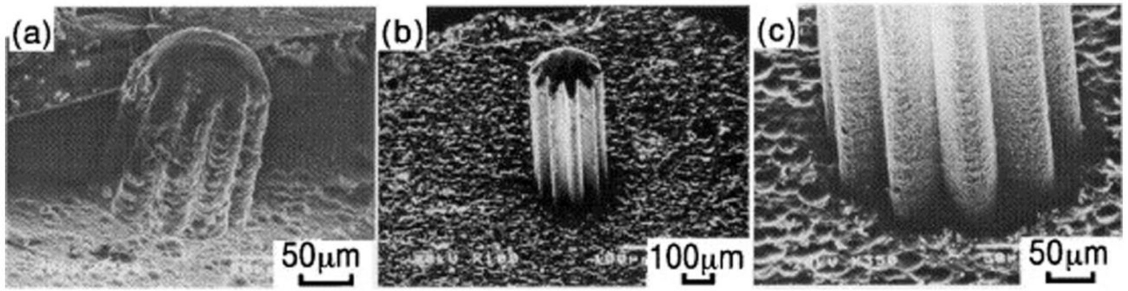
It is considered as a subclass of micro-forging processes (or bulk microforming)

It is a fast process with minimal wastage of raw material and it is suitable for mass production

It is one of the most widely used processes in microforming





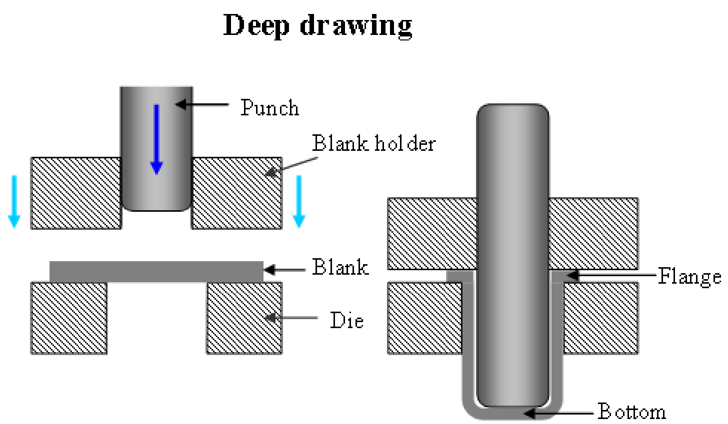


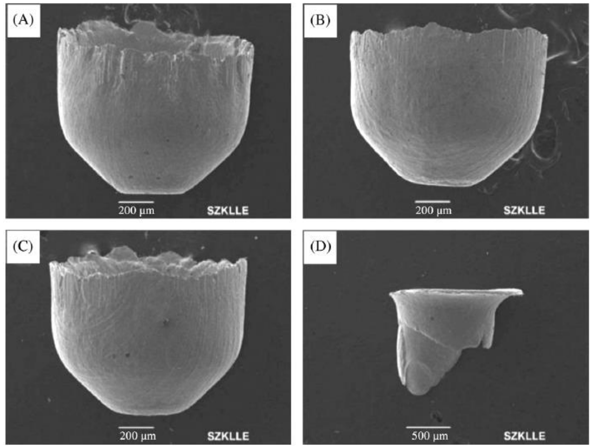
Extruded microgear shafts made of Al-78Zn superplastic alloy (module 10µm and 20 µm)
Saotome and Iwazaki, 2001

Microforming

Some example

Micro-deep drawing





Micro-deep drawing process (Gong et al, 2015)

Deep drawing is the most widely used processes in sheet metal forming

It consists in forming a part named blank (sheet metal part) through of a fixed tool (die) and a mobile tool (punch)

Classicaly the blank is held on the die surface by the way of a third tool named blankholder

The obtained part (flange) is a (very) thin 3D complex component

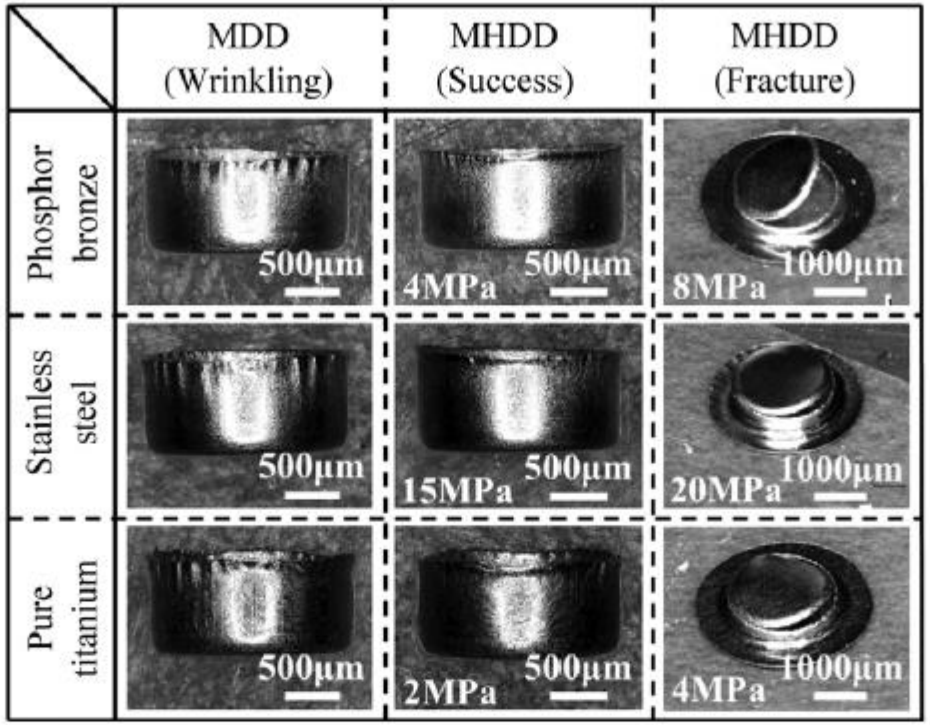
To increase the sheet formability (deformation ability), a multipass deep drawing process is used (reverse or not)

Strain path is a key factor in (micro)-deep drawing

Tools are obtained by micromachining processes (micro-milling, grinding, µEDM, ...)

Some example

Micro-deep drawing



Micro-deep drawing process (Gong et al, 2015)

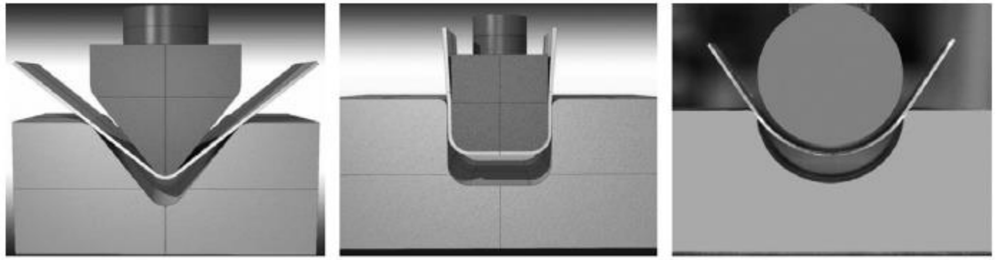
Strain path is a key factor in (micro)-deep drawing

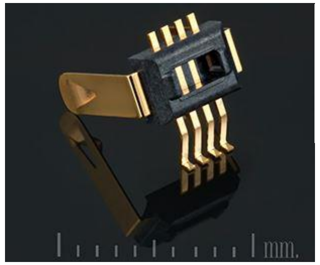
Depending on the strain path undergone by the sheet, defects may appears (wrinkling, fracture, surface quality, necking, springback…)

Tribological behavior in micro-deep drawing is an important factor that may have significant effect on the whole forming process

Some example

Micro bending





Micro-bending is a major process in microforming

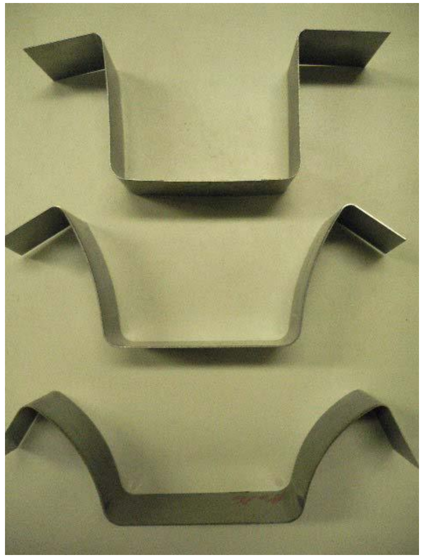
It involves plastic deformation of workpiece over an axis to create change in the part's geometris (V-Shape, U-Shape, cylindrical shape)

Micro-bending process is quite different from the macro one due to the common problem of size effects at microscale

Micro-deep drawing process (Gong et al, 2015)

Some example

Micro bending



Many factors have significant effects on the process and the quality of the bended products :

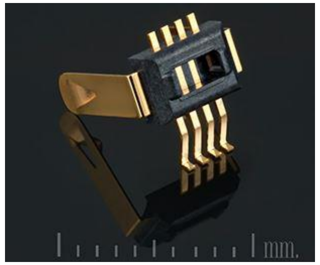
- Thickness of the sheet
- Grain size, shape, orientation an distribution
- Friction and surface quality of the tools
- Clearance between tools and sheet

One of the major challenging issues in micro-bending processes is springback

Springback occurs immediately after the release of the forming force or occurs due to the subsequent release of the residual stresses in the formed parts

It results in a distorsion of the shape obtained after forming or instability of dimensions of the bended part in service (example : pin connectors)

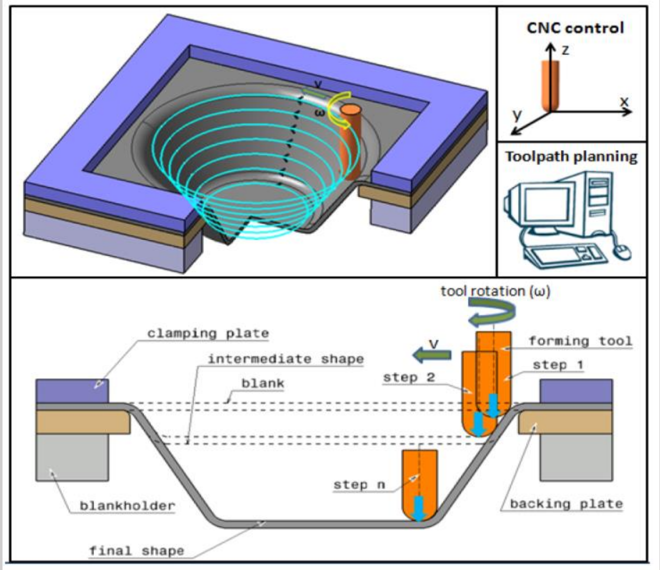
It depends on path strain, friction, elastic-plastic properties, punch and die profile radii, ...



Focus on micro-incremental sheet forming

Principle

Micro Incremental Forming (the process)

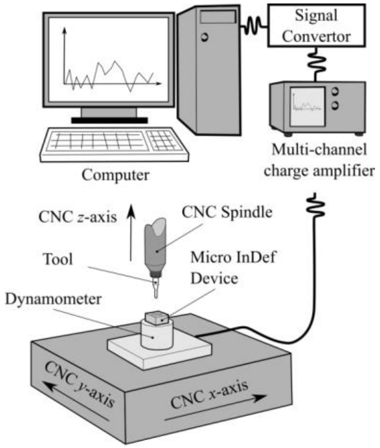


Dieless process : no specifical tools are necessary

- **Die is a simple cavity (no particular feature)**
- **Punch is a simple hemisherical and smooth tool**

By using a CNC Micromilling machine :

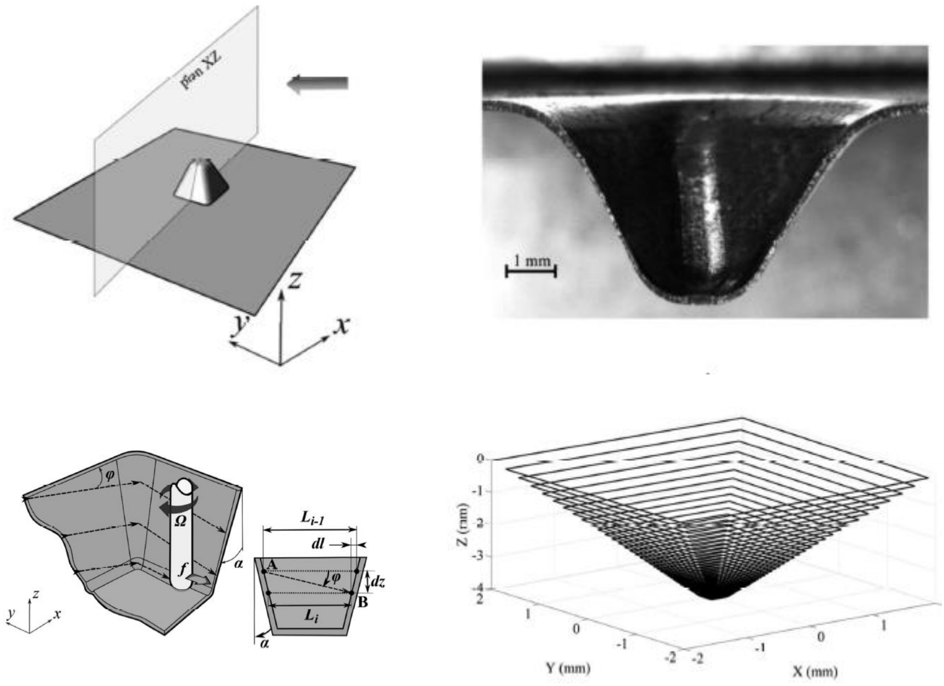
- a very thin metal sheet (or polymer) is fixed on the die surface clamped on the CNC machine table
- Punch is clamped in the spindle of the machine
- A specifical toolpath is generate to deforme locally the part



Microforming

Focus on micro-incremental sheet forming

Example of a pyramid shape obtained by µISF (CuNiP alloy – Thickness : 210µm)

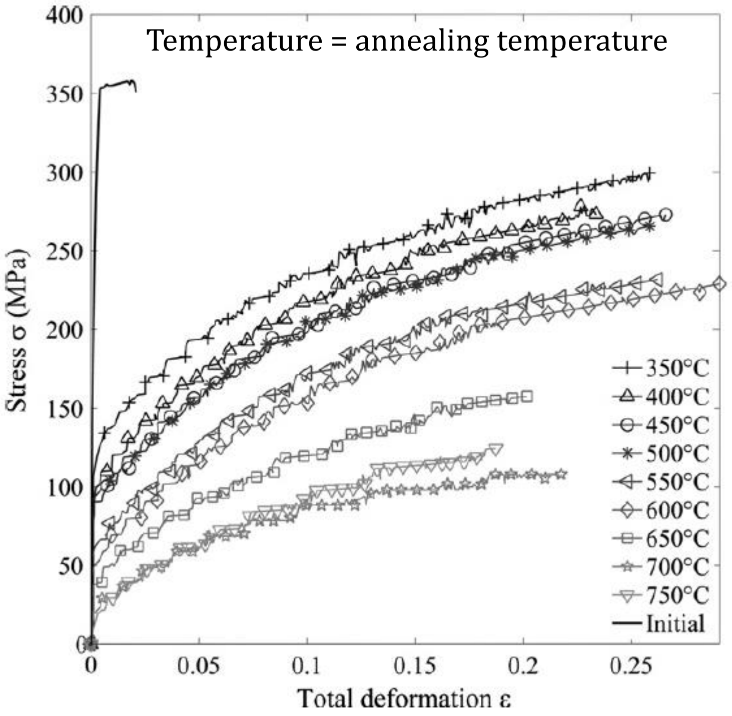


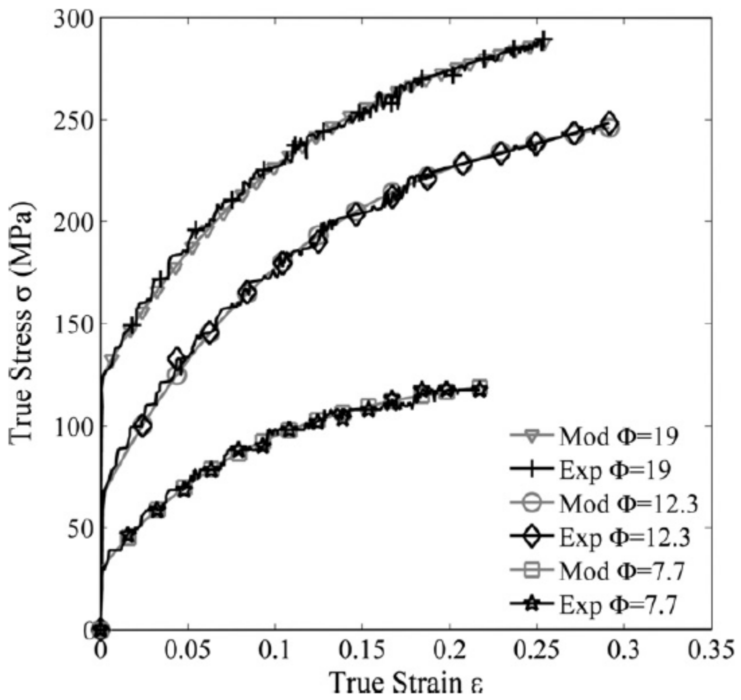
R. Ben Hmida, PhD Thesis, 2014

Microforming

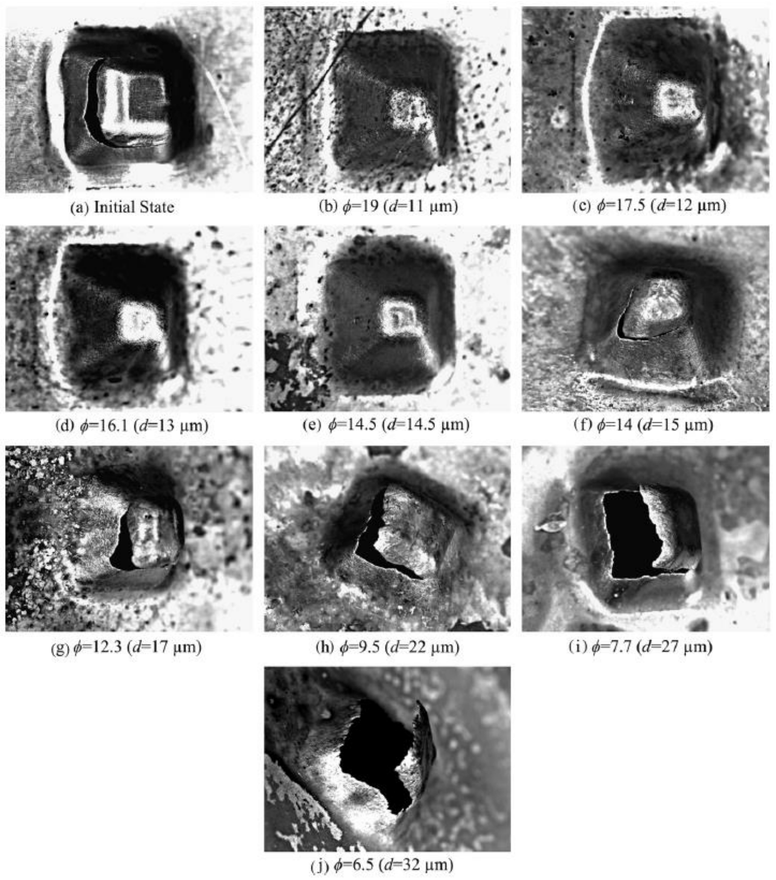
Focus on micro-incremental sheet forming

Merchanical behavior and formability





Flow stress curves



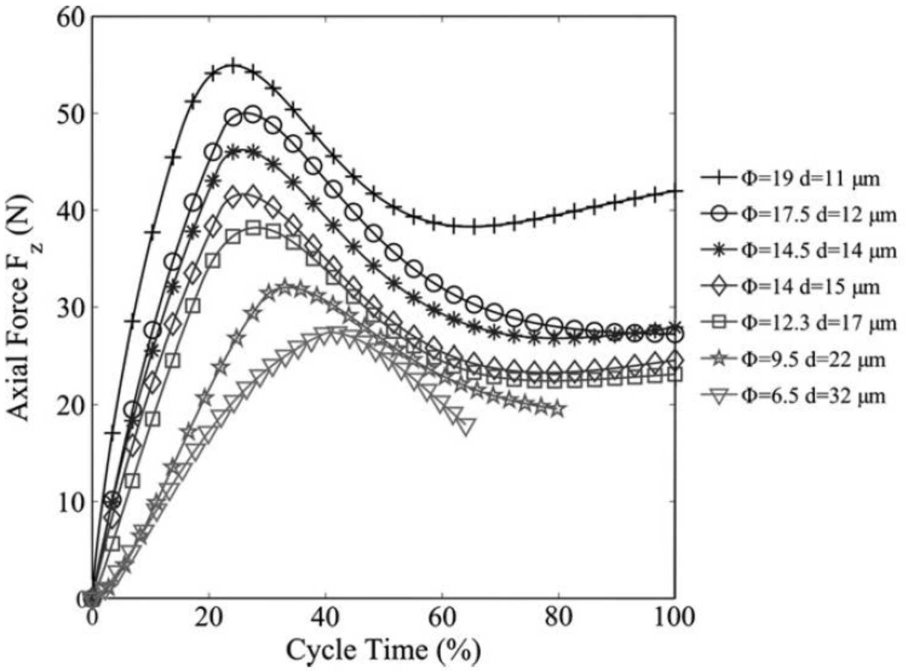
Fracture depends on initial grain size

Hall-Petch effects : Microstructure scale effets

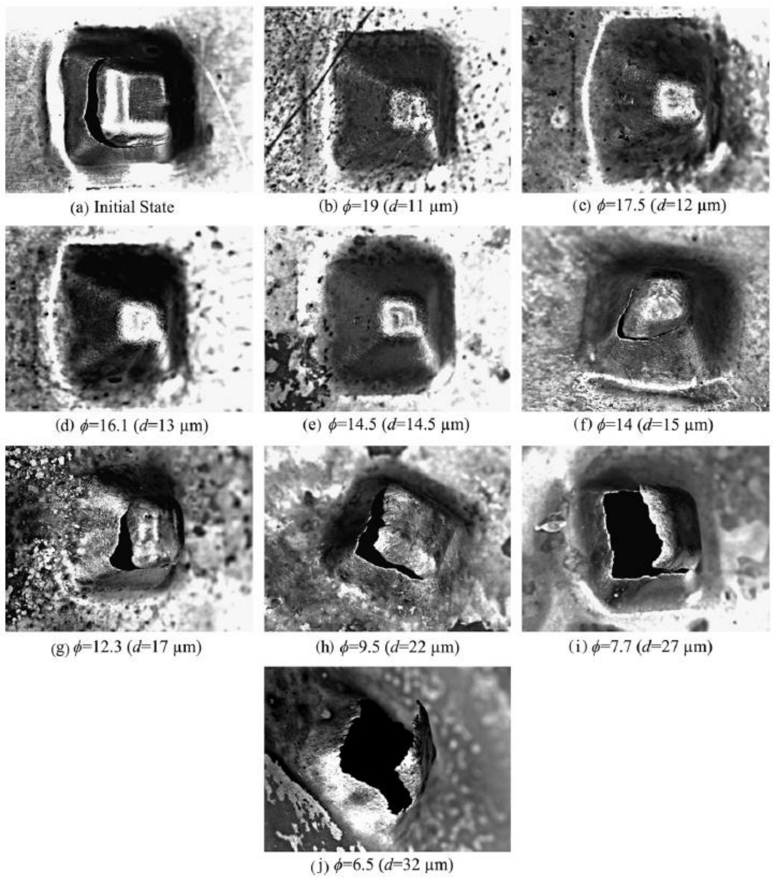
Ben Hmida, Materials and Design, 2013

Focus on micro-incremental sheet forming

Merchanical behavior and formability



Forming forces depends on grain size in the same way as flow stresses curves (Hall and Petch)

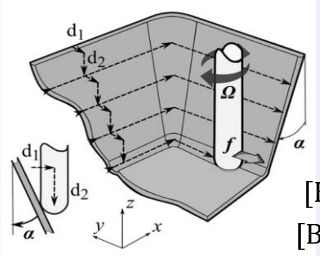
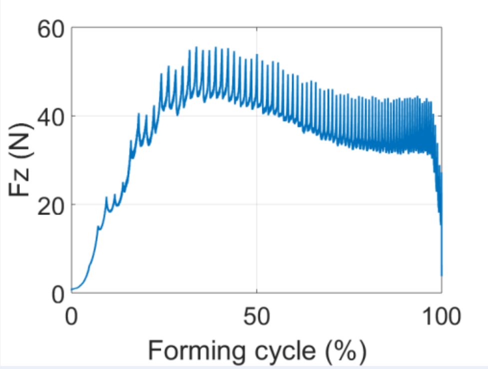


Fracture depends on grain size

Ben Hmida, Materials and Design, 2013

Focus on micro-incremental sheet forming

Is it possible to use µIncremental sheet forming process as a mechanical characterization test ?

Test	Characteristics	Suitable?
Micro Incremental Deformation (µ InDef) test  [Hapsari, 2017] [BenHmida, 2014] 	Specimen geometry: simple	
	Specimen setup: fixing device required	
	Equipment: Micro milling machine, dynamometer	
	Deformation type: heterogeneous & out-of-plane	
	Deformation measurement: none	In progress
	Maximum strain: 250%	
	Extracted experimental data: requires **FEMU for analysis**	
	Complex experimental setup (forming path, dynamometer, amplifier, post treatment)	

Focus on micro-incremental sheet forming

Identification procedure

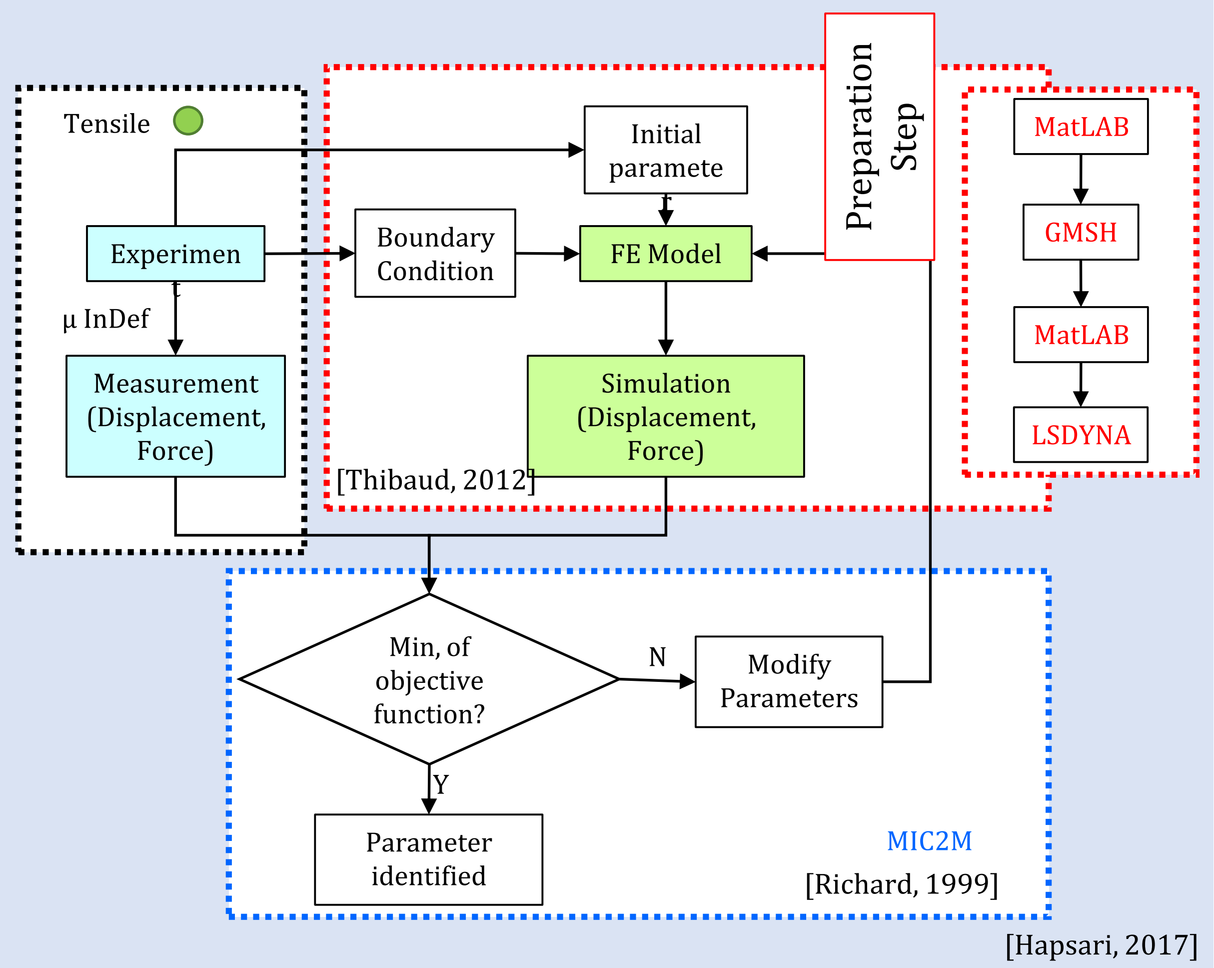
Is it possible to identify an elastic plastic damage coupling Lemaître-type model **in large deformation context** (more than 200%) ?

Needs an equivalent Finite Element Model

Comparison of axial forming forces (experiments and numerical)

Minimization procedure to obtain model parameters

Identifiability method to validate model parameters (identification or fitting ?)



Ben Hmida, Materials and Design, 2013

Microforming

Focus on micro-incremental sheet forming

Numerical model

FE Model in large deformation context with a elastic plastic damage coupling Lemaître-type model

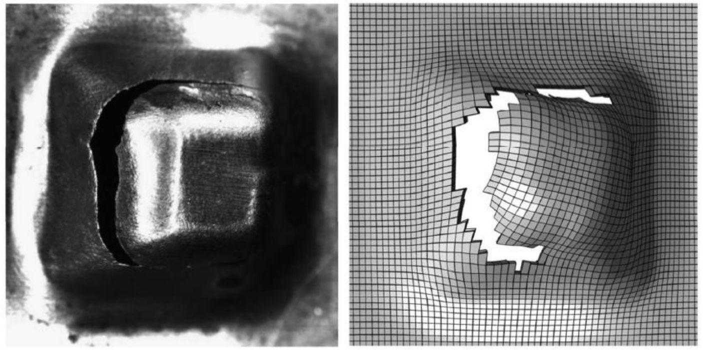
3D Solid elements (under integrated elements)

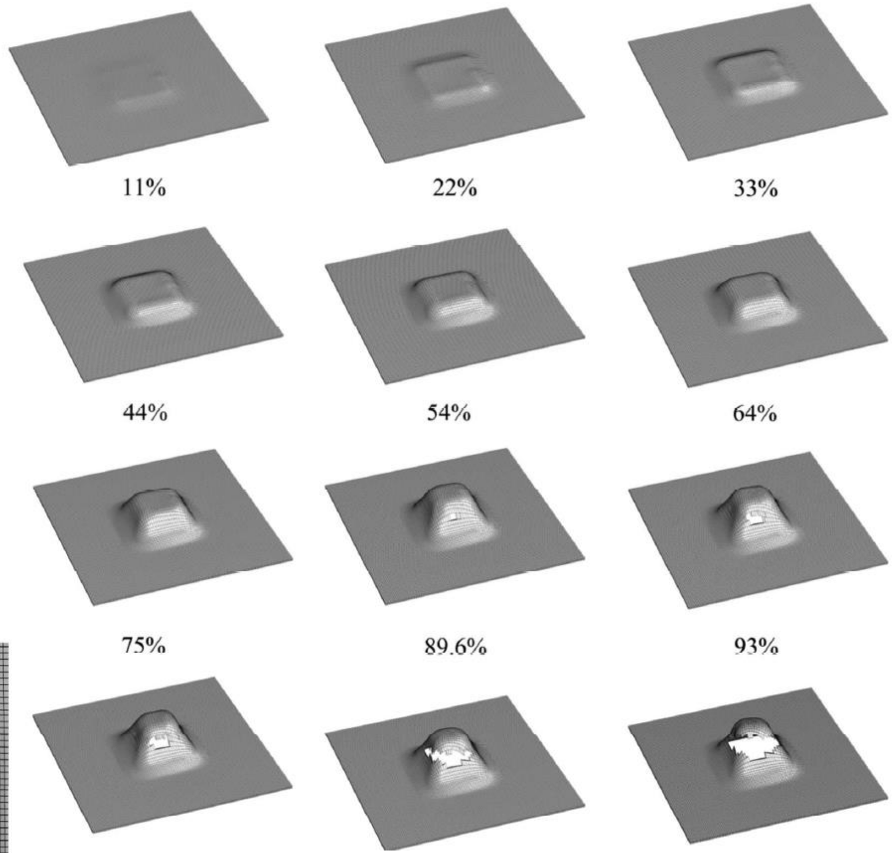
Penalty contact algorithm

Explicit Dynamic Integration time algorithm (LS-DYNA)

CPU Time : 8 hours with 8 CPUs

Tools : rigid shell elements





[Thibaud, 2012]

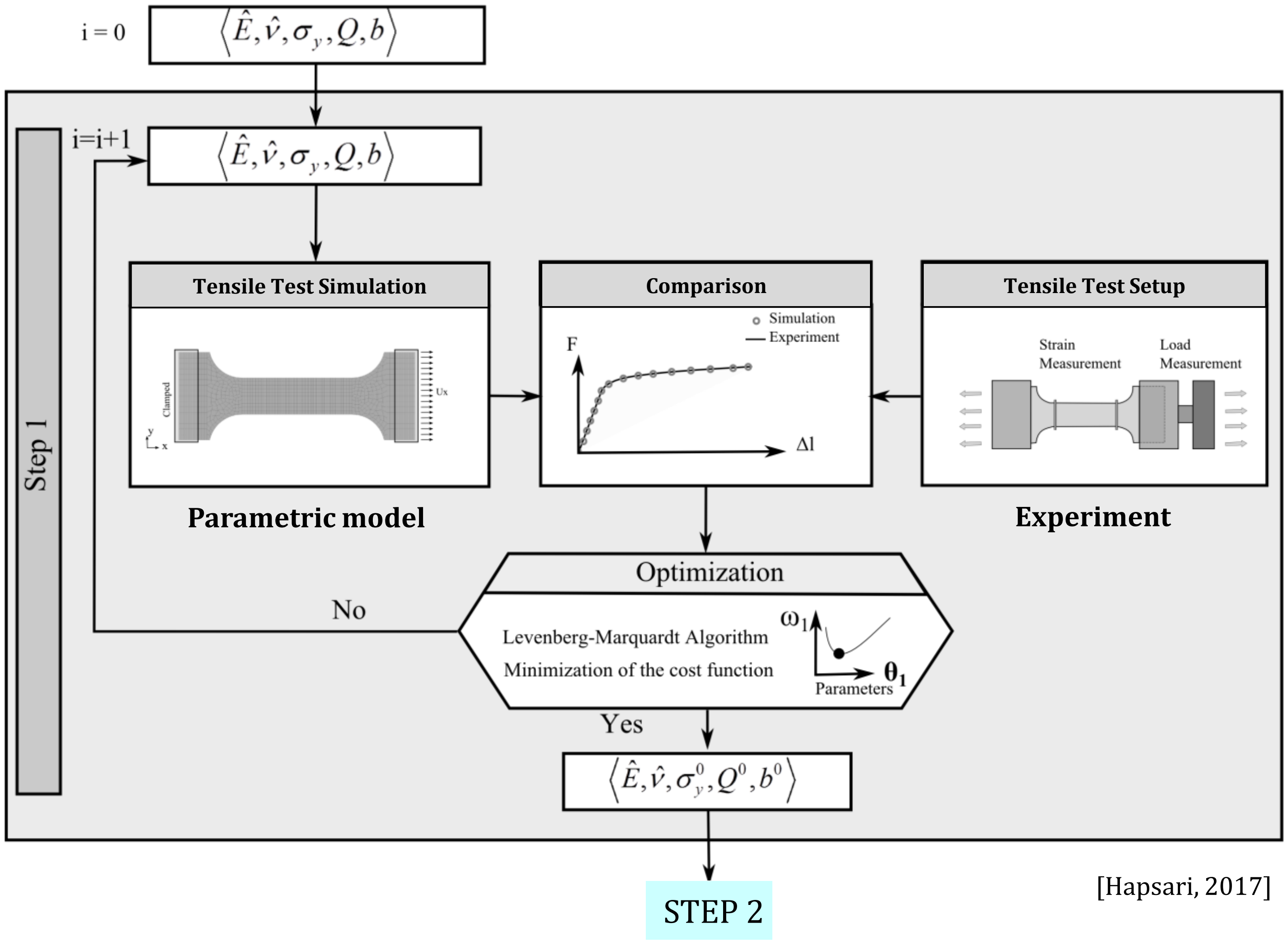
Focus on micro-incremental sheet forming

Identification procedure

STEP 1 : Minimization procedure by comparing tensile tests (experiments and model)

Aims :

- Determine a first set of parameters values to decrease identification procedure (Elastic-Plastic values)



[Hapsari, 2017]

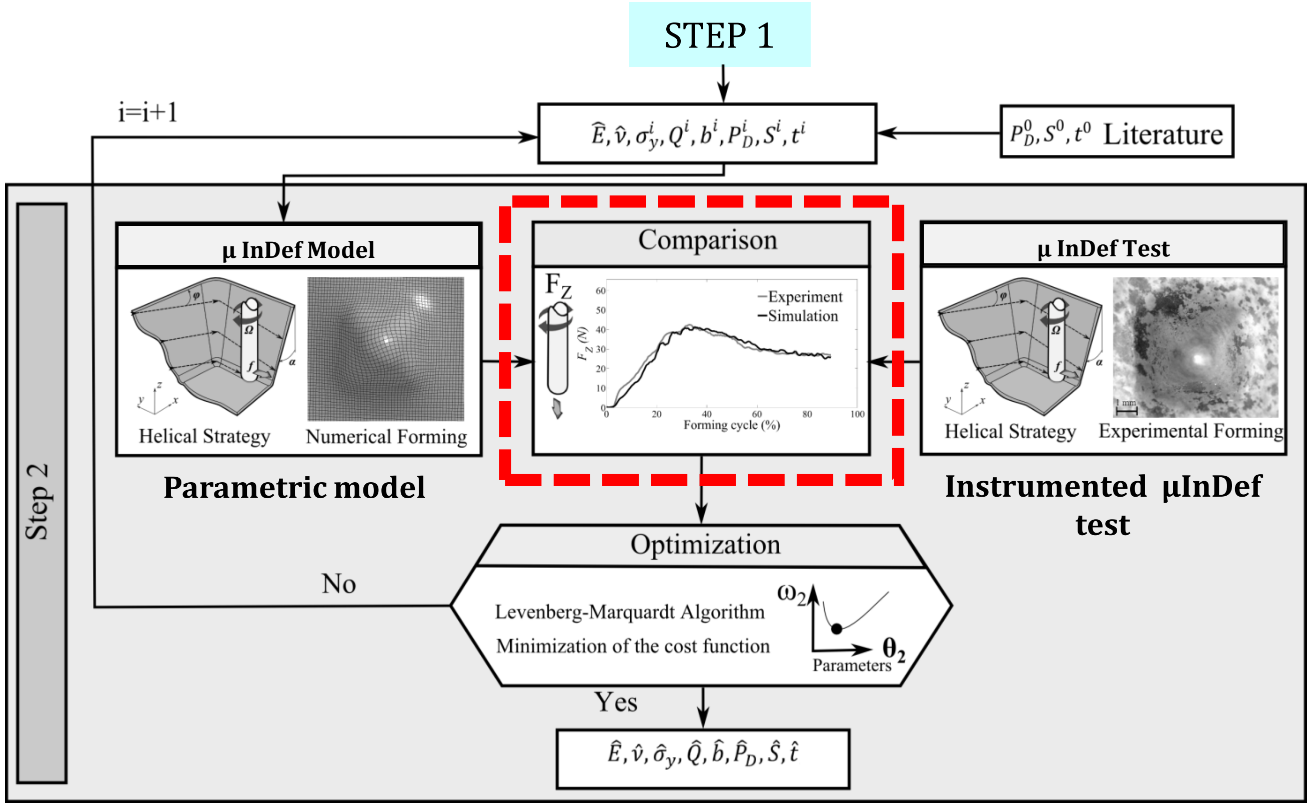
Focus on micro-incremental sheet forming

Identification procedure

STEP 2 : Minimization procedure by comparing μISF tests (experiments and model)

Aims :

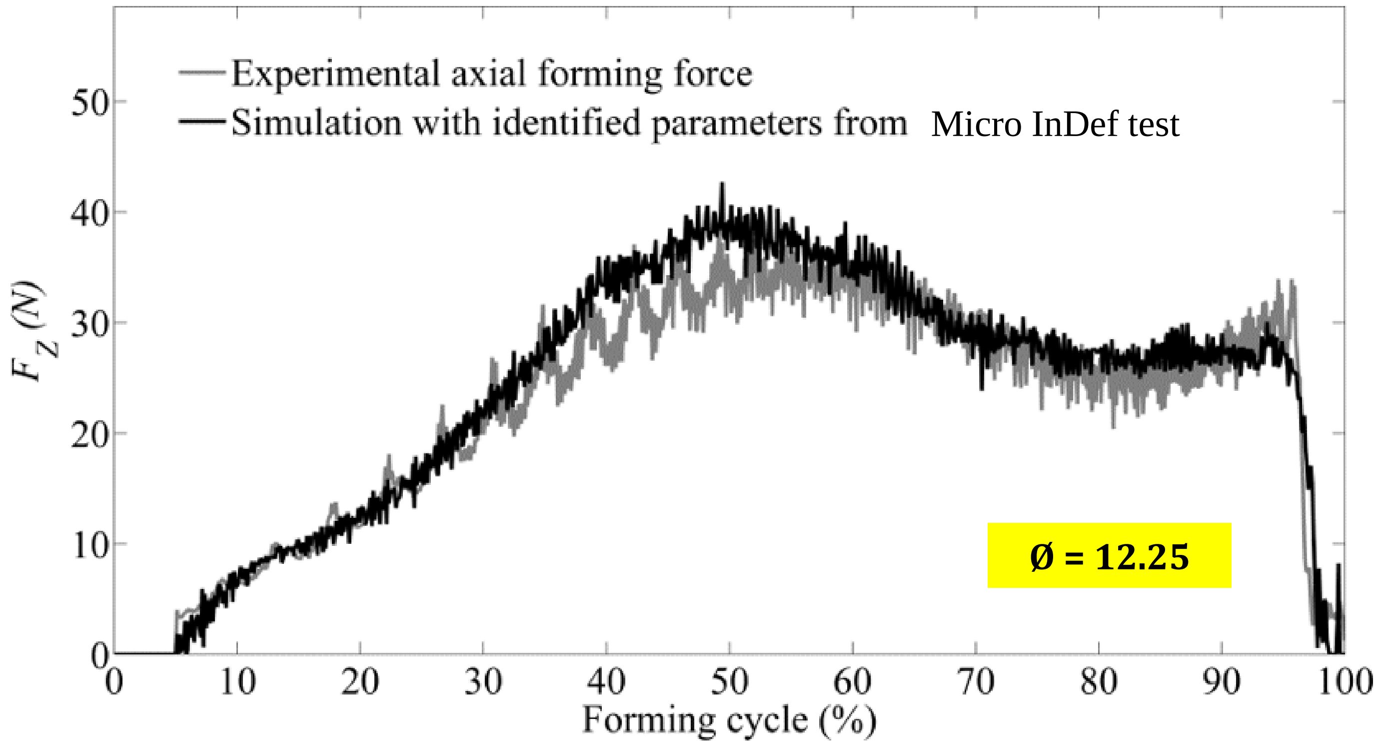
- Determine the physical set of parameters values to decrease identification procedure (Elastic-Plastic values and Damage evolution)



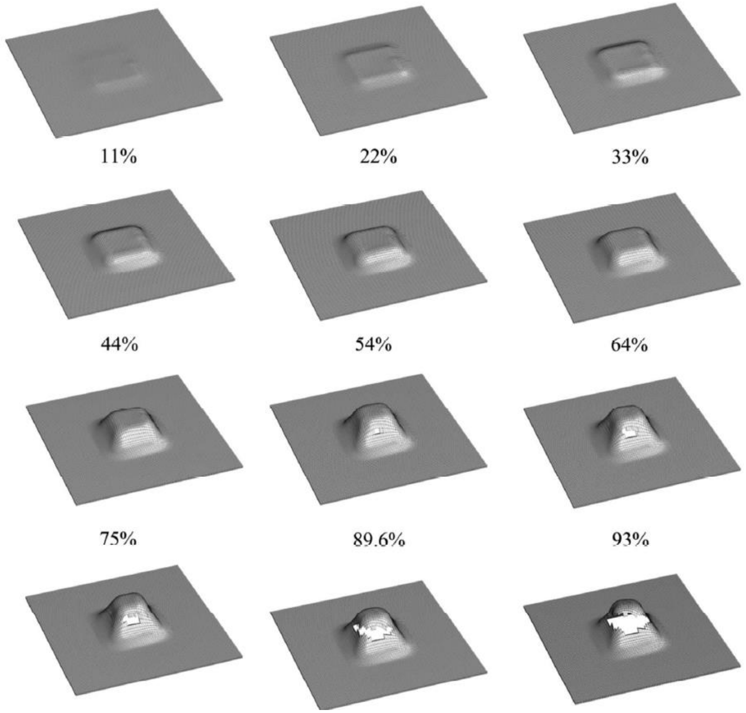
Ben Hmida, Materials and Design, 2013

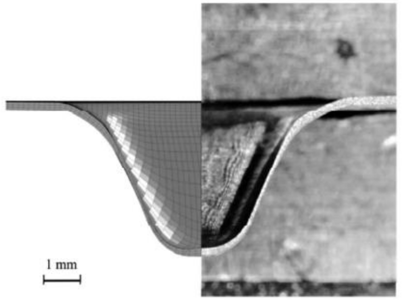
Focus on micro-incremental sheet forming

Identification procedure - Results



Ben Hmida, Materials and Design, 2013

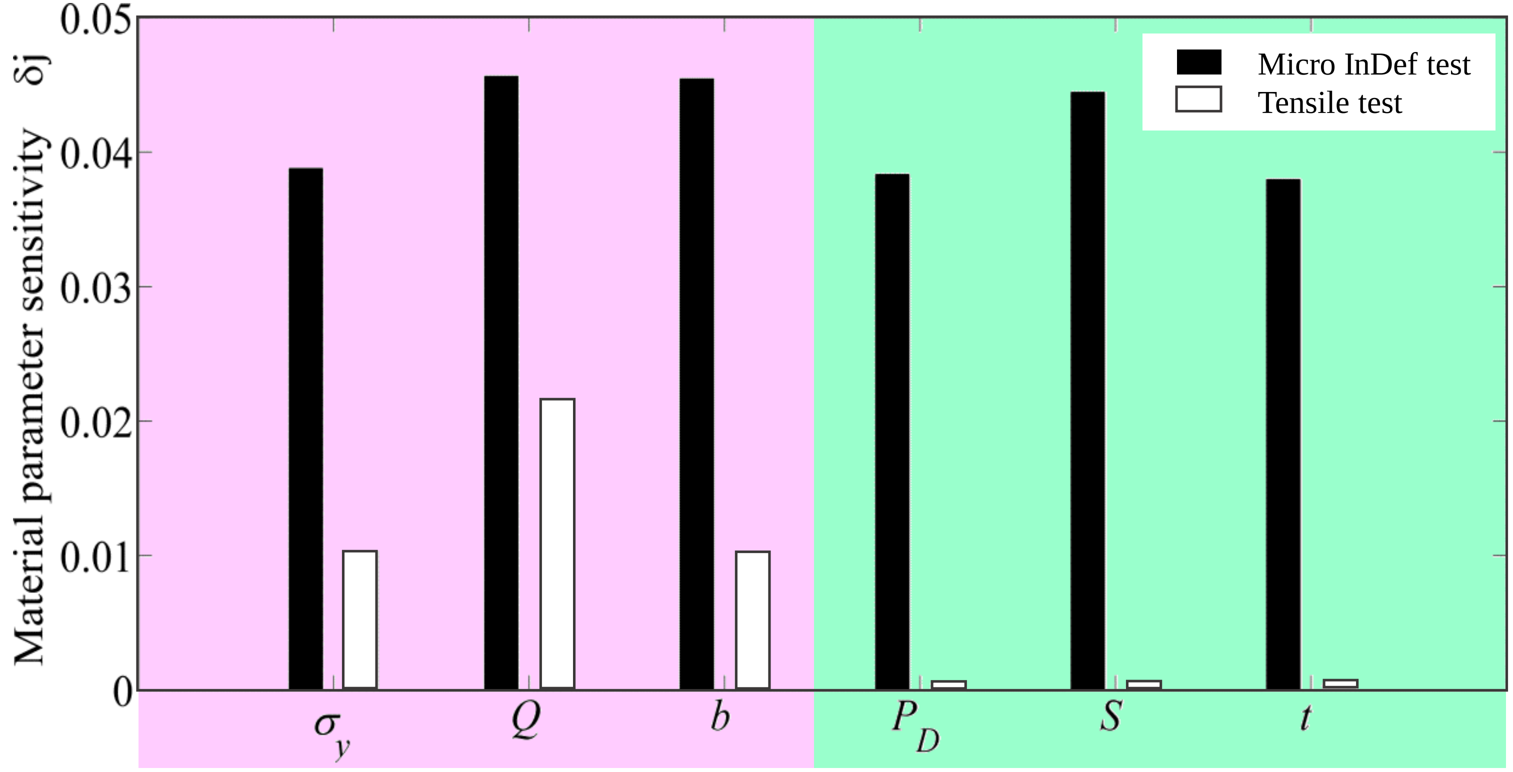




Microforming

Mathematical fitting ? Sensitivity analysis

Sensitivity of the Axial Forming Force according to the Material



Micro InDef Test
➔ Each sensitivities are equivalent in magnitude

Plastic	**σ_y**	Initial Yield Strength
	Q	Saturation Value (Voce Hardening Law)
	b	Hardening Exponent (Voce Hardening Law)
Damage	**P_d**	Accumulated Plastic Strain Threshold
	S	Damage Strength
	t	Damage Material Constant

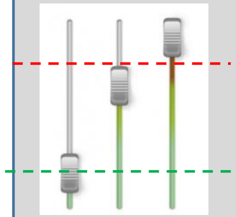
Tensile tests response is not sensitive to damage parameters (not identifiable here)

Mathematical fitting ? Identifiability method

The axial forming force is **sensitive** to parameters

→ **necessary but not sufficient condition !**

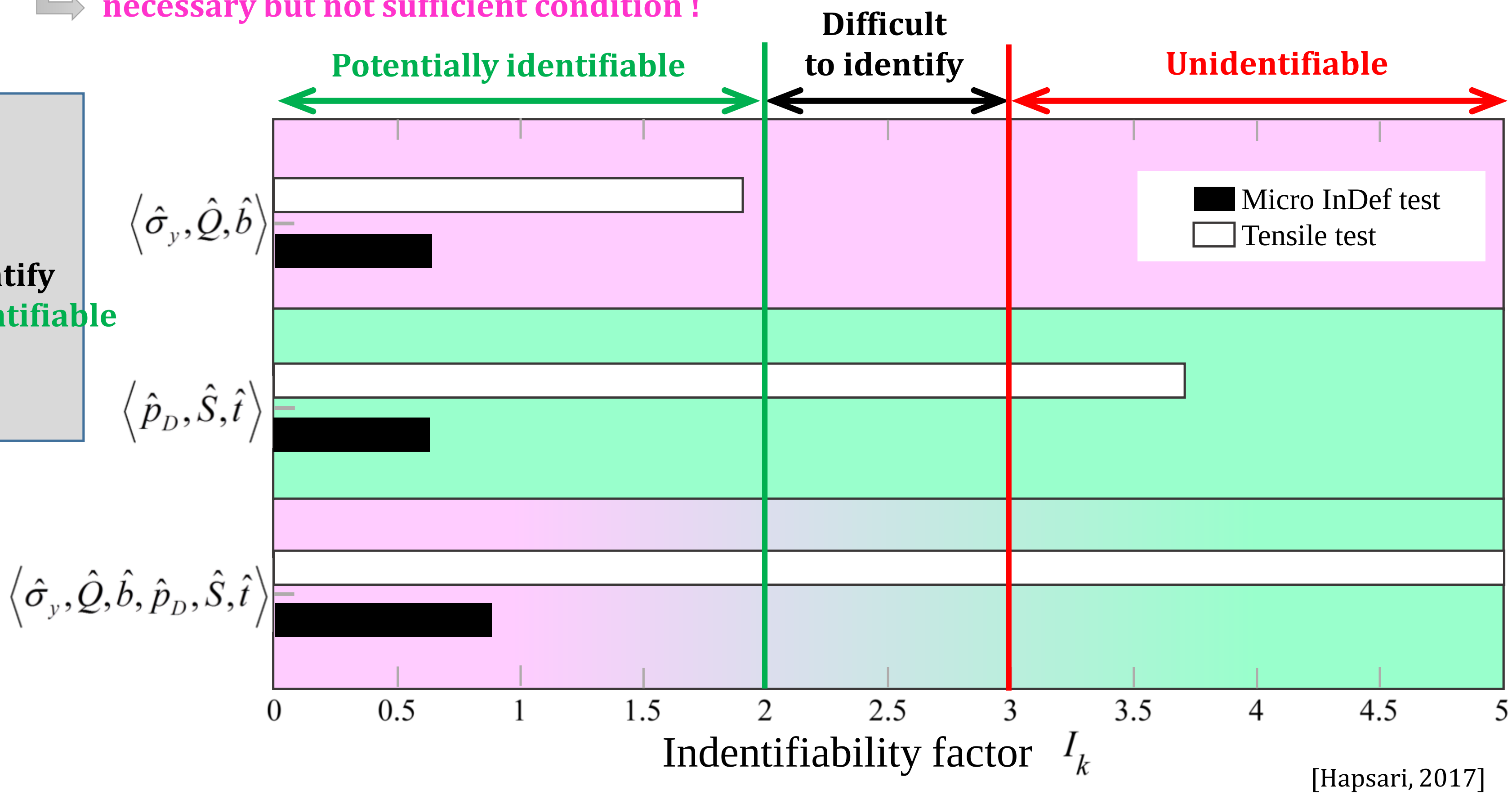
Identifiability Index



> 3 unidentifiable
2-3 difficult to identify
<2 potentially identifiable

[Richard, 2013]

Not mathematical fitting



[Hapsari, 2017]

µIncremental Sheet forming as a new characterization test at microscale

How to characterize the mechanical behavior of very thin copper alloys sheet metal?

By using Micro InDef Test on elastic plastic damage coupling model of Lemaitre

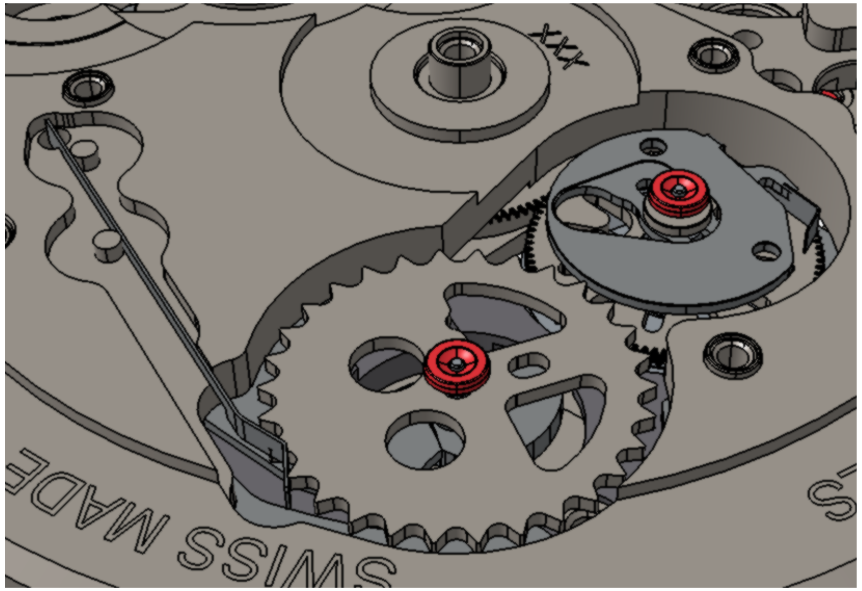
Will we obtain a set of reliable results?

By choosing the smoothing axial forming force which is sensitive to material parameters & proven identifiable.

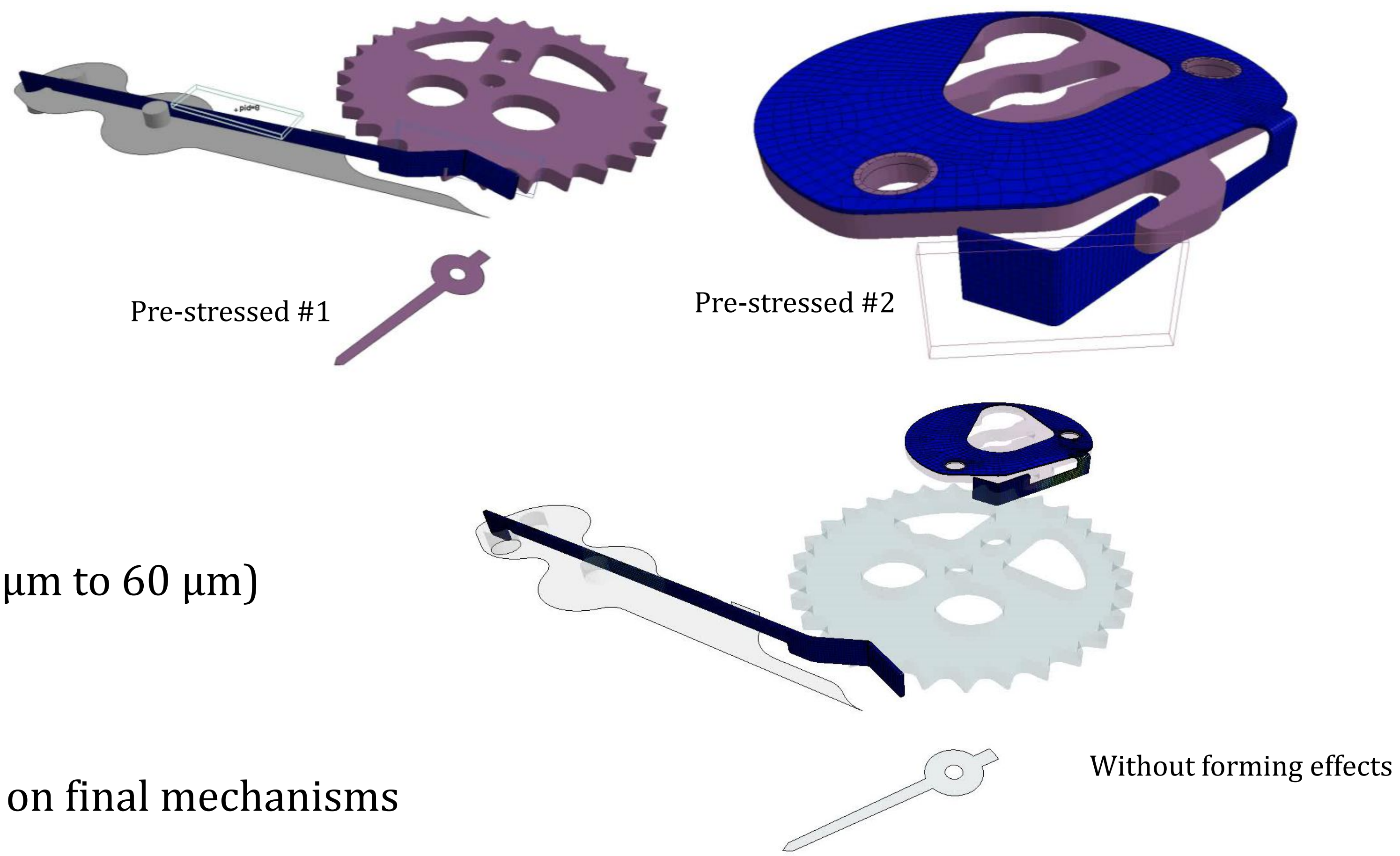
why finely characterize the behavior of sheets at these scales ?

Application

Application to the development of an indexing system



Chain complex non-linear numerical models



Very thin metal sheets for springs (from 35 µm to 60 µm)

Very accurate performances are specified

Influence of micromanufacturing processes on final mechanisms

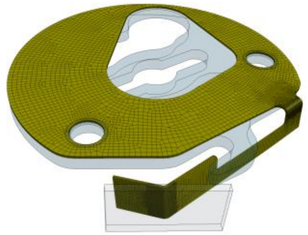
Application

Application to the development of an indexing system

Taking into account microforming effects ?

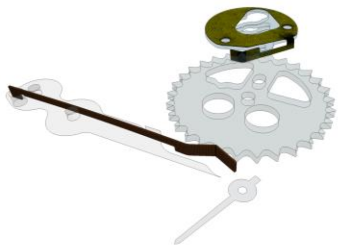
Without MEF Effects

Assembly



Elastic behavior

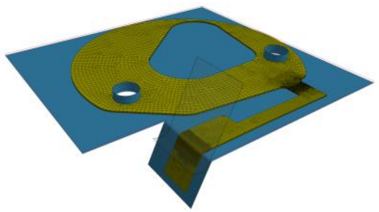
Simulation



Elastic Behavior

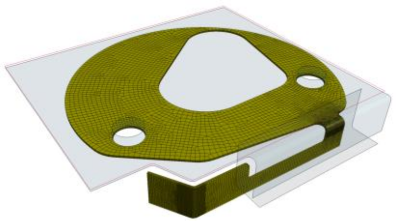
With MEF Effects

Forming #1 + Spg #1



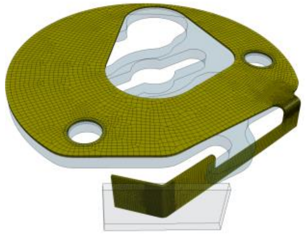
Elastic-plastic behavior

Forming #2 + Spg #2



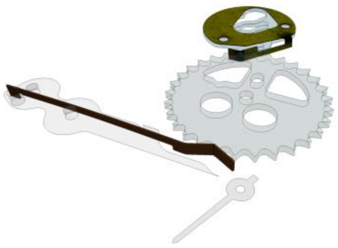
Elastic-plastic behavior

Assembly



Elastic behavior

Simulation

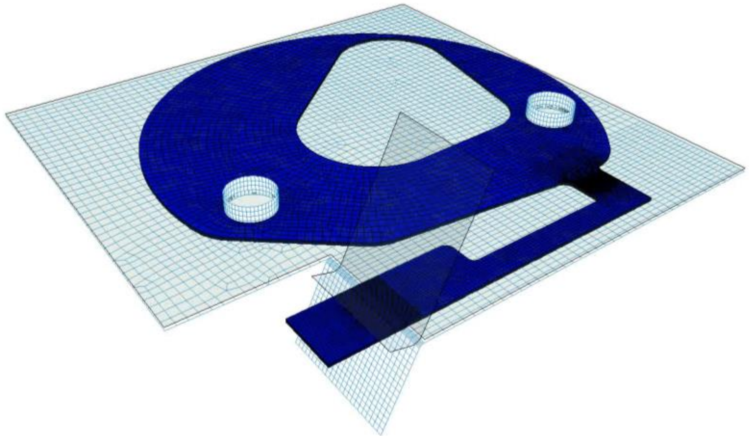


Elastic behavior

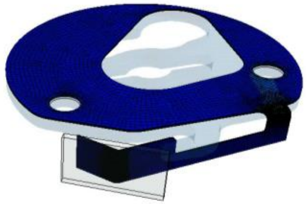
Application

Application to the development of an indexing system

Microforming and defects (springback)



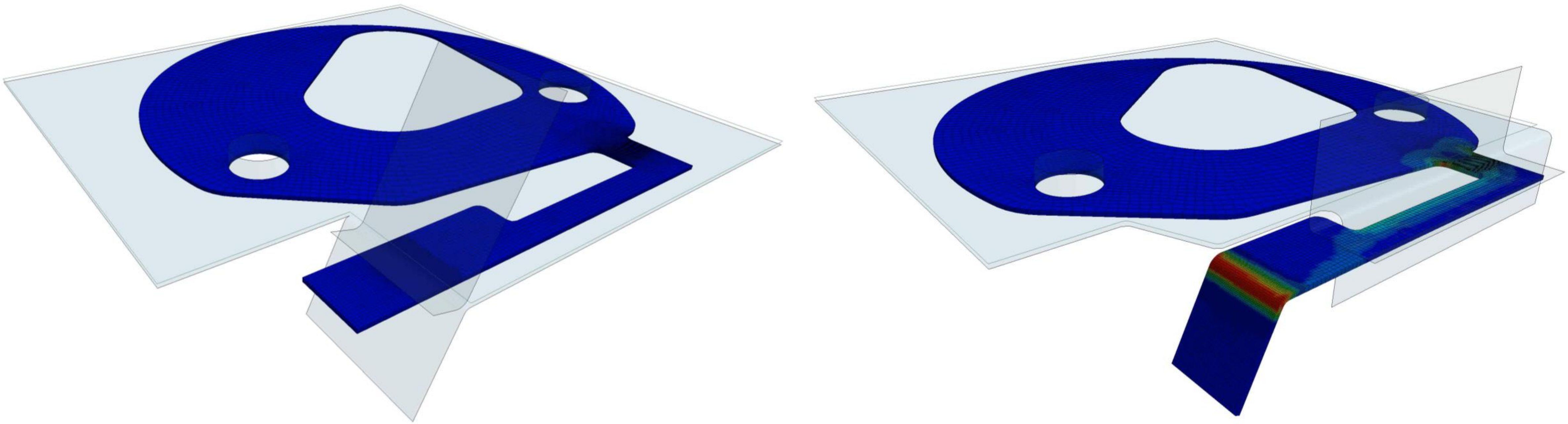
Introducing microforming effects in mechanism simulations



Microforming effects ? A major influence especially due to hardening paths and their influences on springback

Application

Springback ?

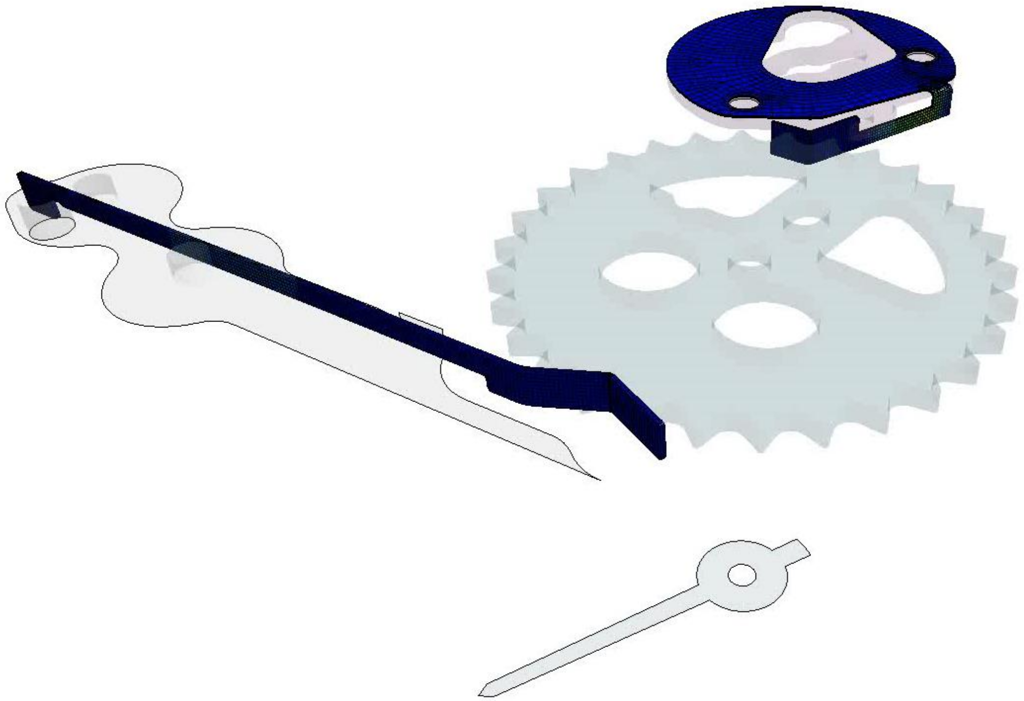


Complex strain paths and high friction interfaces effects are introducing during microforming processes
After tools removing : the elastic energy is released and a shape variation is observerd = springback

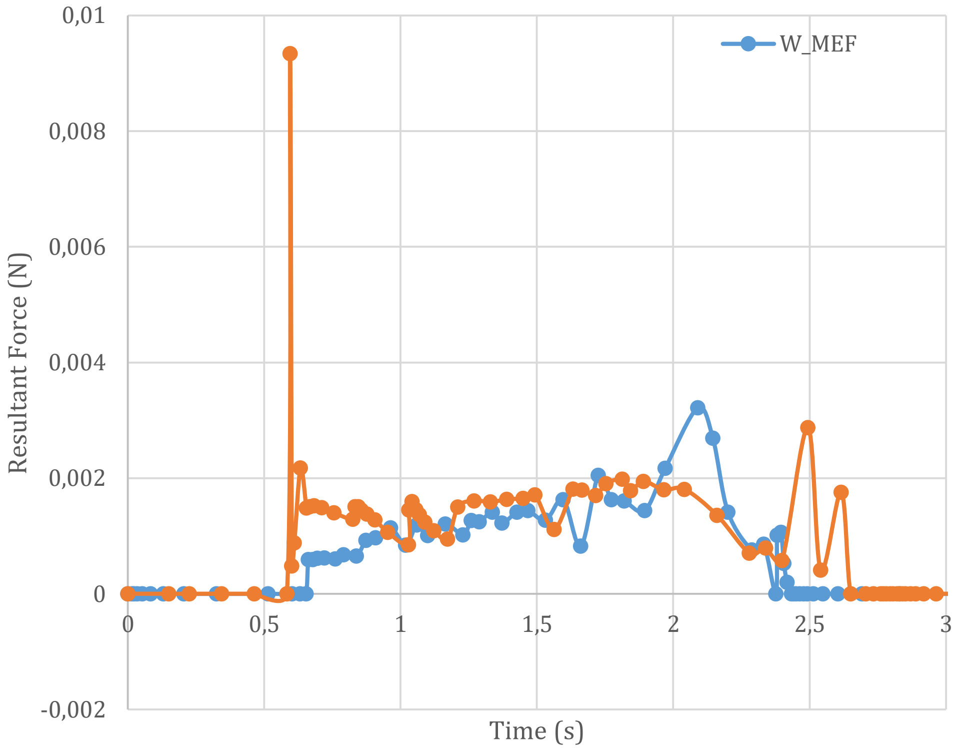
It's necessary to predict these influences to modify microforming processes

Application

Influence ?



Comparison between with/without microforming effects on contact forces in the indexing mechanisms



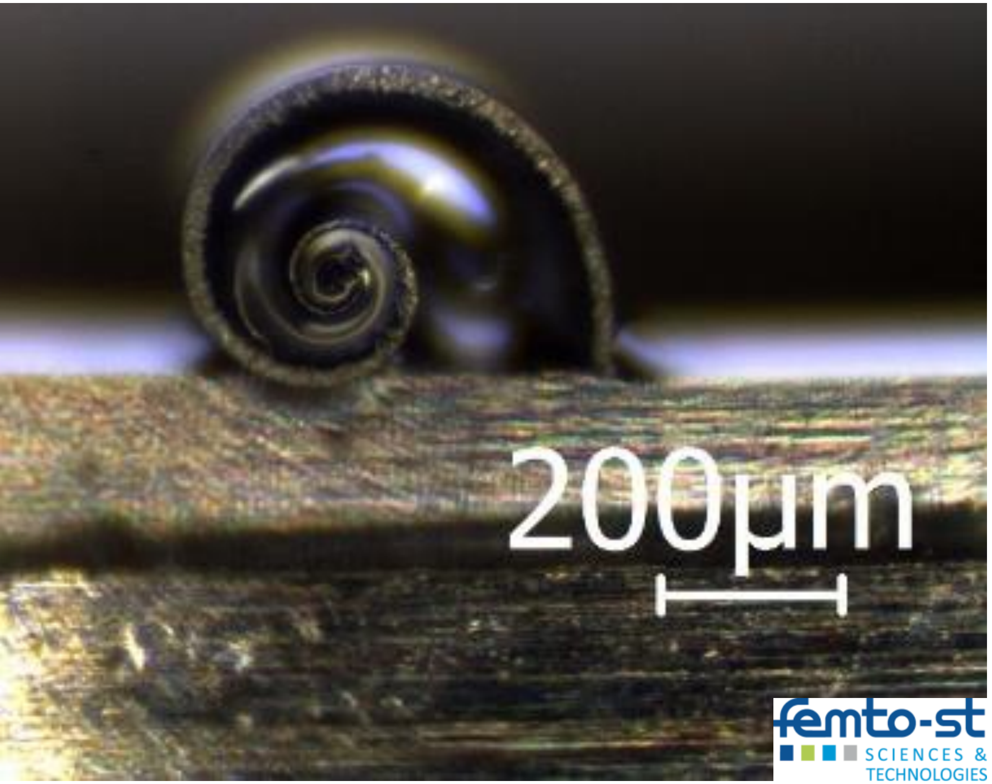
Microforming

Application

Microforming processes introduce

- Complex strain paths
- High strains / stresses / displacements / rotations
- Elastic-Plastic / viscoplastic behaviours (time dependant problems)
- Friction at interface is very important at micro-scale
- The mechanical behavior of very thin sheets/foils is very dependant of the initial/current grain size
- Very thin sheets anisotropy is quite soon important

Methods to characterize very thin sheets are necessery and it is always an open problem today (see S. Thuillet Phd thesis)



R. Piquard – PhD Thesis – FEMTO-ST - 2016

Micromachining

Traditional Removal Processes

Micromachining

Micromachining is the removal of material in the form of chips or debris with sizes in the range of microns

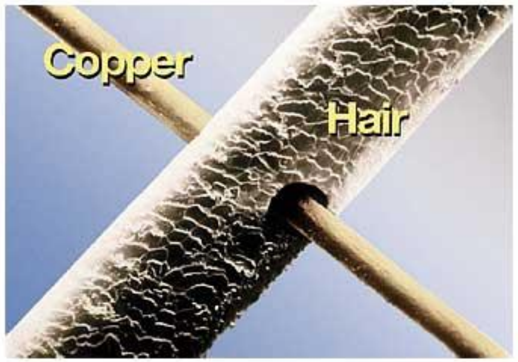
- Greater than one micron
- Smaller than one millimeter

It consists of creating microfeatures on macro- or microcomponents

Subtractive-type micromanufacturing processes are classified into two classes :

- Traditional micromachining processes
- Advanced micromachining processes

Traditional Micromachining : Drilling



Hair Drilling

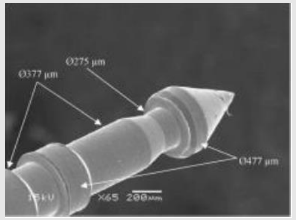
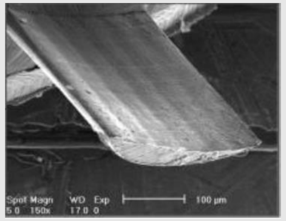
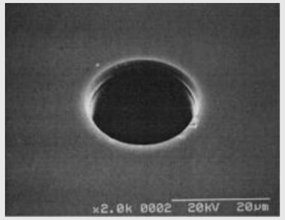
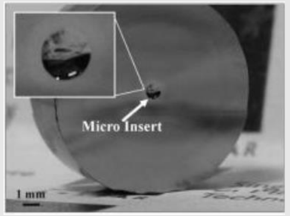
Traditional Micromachining : Micromilling

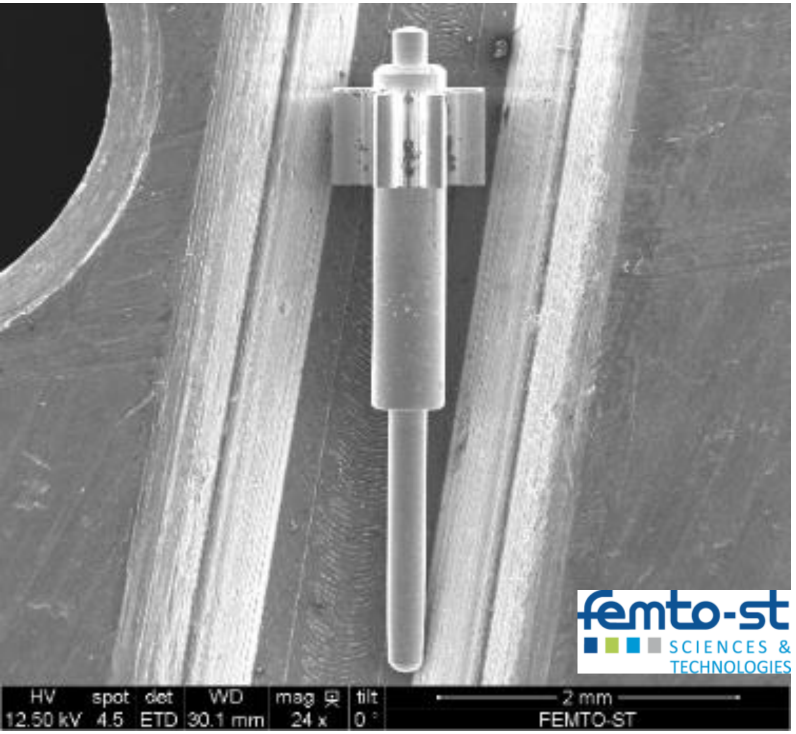
Hair Milling

Advanced Micromachining : Wire Electrical-Discharge Machining

Cochlear implant

Micromachining - Applications

	Micro-turning	Micro-Milling	Micro-Drilling	Micro-Grinding
Typical part	Revolution parts (long axis)	3D Complex shapes parts (convex or concave) – thin shapes	Blind or free holes	Concave and convex geometries can be achieved Adapted to hard and brittle materials
Typical geometrical dimension	Diameter from 100 µm up to 5 µm	Near 50 µm	Up to 10 µm	Up to 20 µm
Minimal Surface rugosity	0.1 µm Ra 10 nm Ra (from diamond turning)	10 nm Ra (for optical finishing with diamond tools)	0.1 µm Ra	10 nm Ra (optical finishing)
Exemples				
	Rahman et al., 2005	Bang et al., 2004	Egashira et al., 2002	Chen et al., 2005



B. Escolle – Post Doctoral position – 2016-2018

Precision Swiss Turning

Traditional Removal Processes

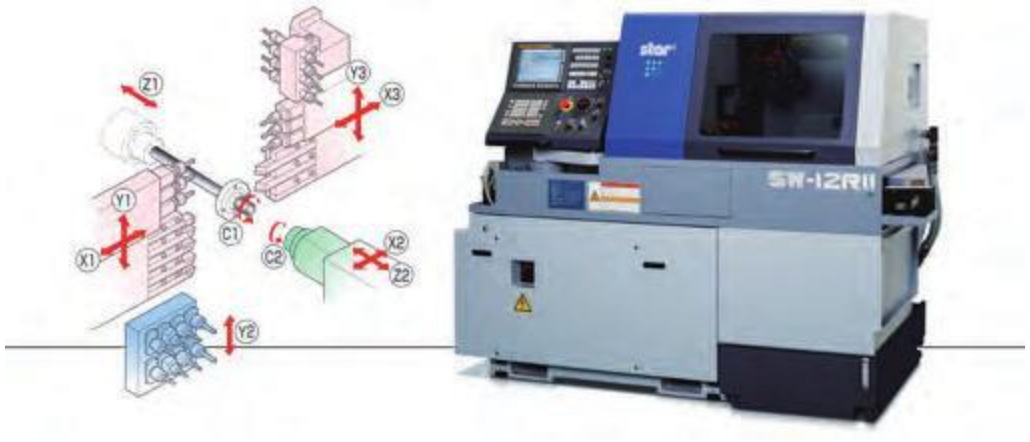
Precision Micro Swiss Turning

Precision Micro Swiss Turning is certainly the most micro-turning process known

- A bar (not necessarily cylindrical one) moves along and rotates in a spindle
- Machining is performed from classical or specifical tools (drill, reamer, tapper, cutter, trimmer, …)
- Highly productivity process : in principle not for prototyping …
- Due to the fact that the bar can move along the spindle, it is possible to perform very long axis nor small diameters or shapes -> Micro-turning
- Traditionnaly, it is used in dental application, watchmaking industry, automotive, … (versatile process)
- It is more than a micro-turning process (in the same machine : drilling, reaming, taping, trimming, milling, …)

Precision Swiss turning CNC Machines with bar feeders (Star)

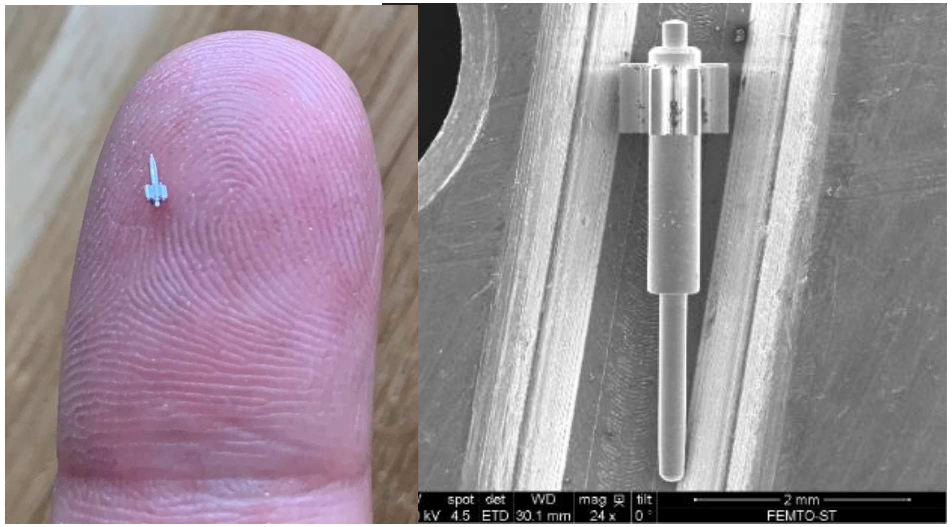
Bar feeders (Star)



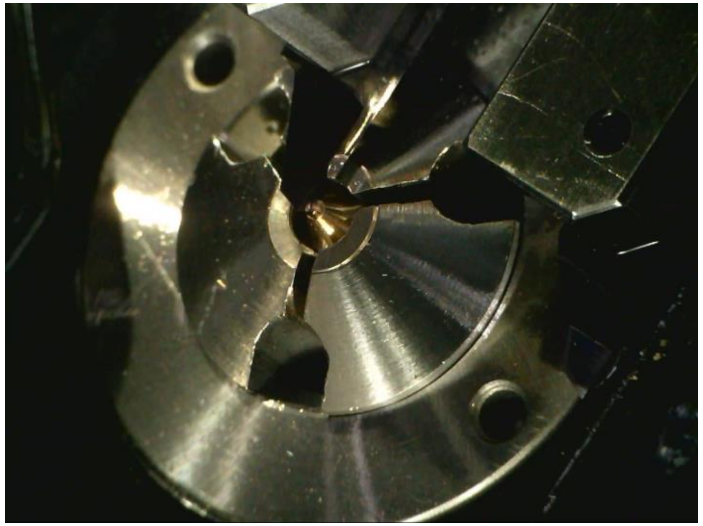
Kinematics description of a 10-axis CNC Precision Swiss Turning Machine (Star SW-12R11)

Precision Micro Swiss Turning

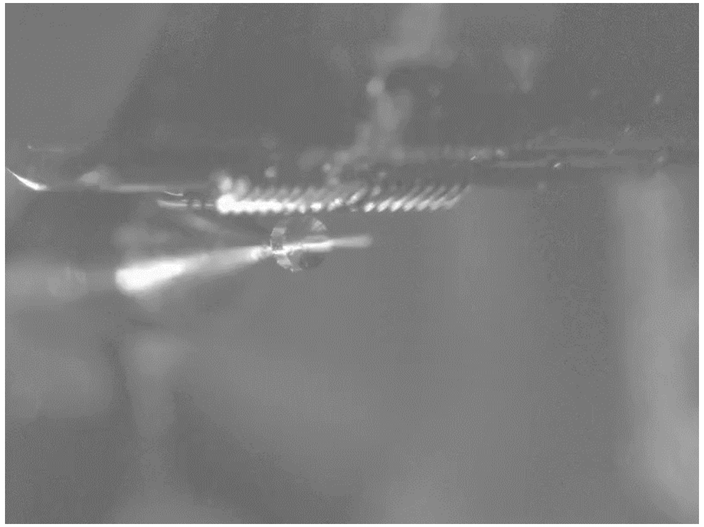
Example : A watch component in hard material (55HRc) by Precision Micro Swiss Turning - µD² Project



Example of a repeat-minuter watch axis
µD² Project – FEMTO-ST – 2015-2019



Axis machining
Reminder : axis diameter is equal to 200 µm (hair diameter)

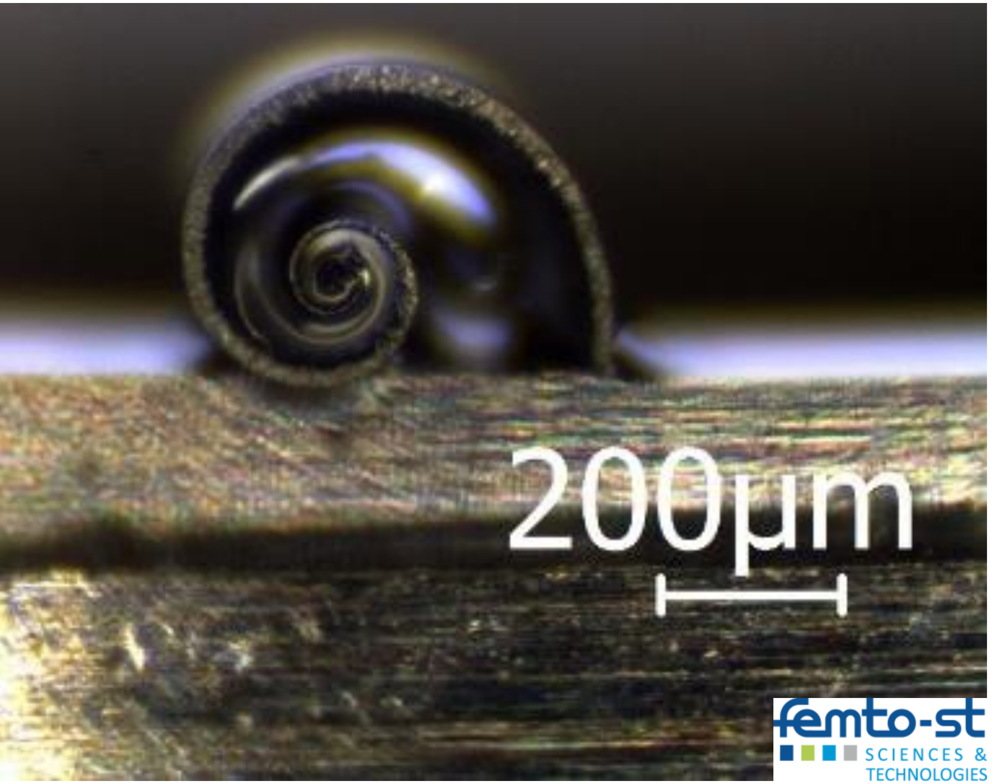


Zoom in on the trimming operation - 5000 fps
Indexation between tool and spindle at 6000rpm

Berenger Escolle – Post Doctoral work – 2016-2018

Scientific locks :

- Understand cutting phenomena at micro-scale in hard materials
- Process Instrumentation at high speed and low cutting forces with accuracy
- Vibration and geometrical defects
- Modelling ?



R. Piquard – PhD Thesis – FEMTO-ST - 2016

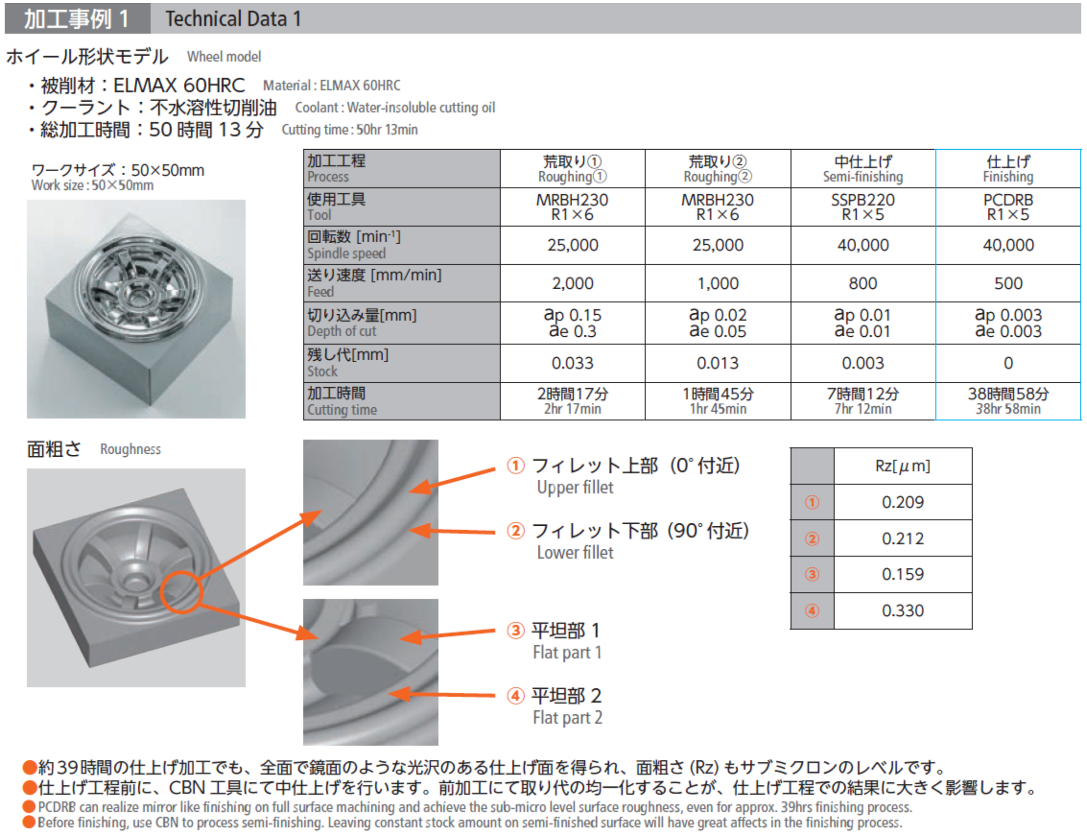
Micromilling

Traditional Removal Processes

Micromilling process

Milling at micro-scale

Five axis micromachining – (Kern)



加工事例 1　Technical Data 1

ホイール形状モデル　Wheel model

- 被削材：ELMAX 60HRC　Material : ELMAX 60HRC
- クーラント：不水溶性切削油　Coolant : Water-insoluble cutting oil
- 総加工時間：50 時間 13 分　Cutting time : 50hr 13min

ワークサイズ：50×50mm
Work size : 50×50mm

加工工程 Process	荒取り① Roughing①	荒取り② Roughing②	中仕上げ Semi-finishing	仕上げ Finishing
使用工具 Tool	MRBH230 R1×6	MRBH230 R1×6	SSPB220 R1×5	PCDRB R1×5
回転数 $[min^{-1}]$ Spindle speed	25,000	25,000	40,000	40,000
送り速度 [mm/min] Feed	2,000	1,000	800	500
切り込み量[mm] Depth of cut	ap 0.15 ae 0.3	ap 0.02 ae 0.05	ap 0.01 ae 0.01	ap 0.003 ae 0.003
残し代[mm] Stock	0.033	0.013	0.003	0
加工時間 Cutting time	2時間17分 2hr 17min	1時間45分 1hr 45min	7時間12分 7hr 12min	38時間58分 38hr 58min

面粗さ　Roughness

	Rz[μm]
①	0.209
②	0.212
③	0.159
④	0.330

- 約 39 時間の仕上げ加工でも、全面で鏡面のような光沢のある仕上げ面を得られ、面粗さ (Rz) もサブミクロンのレベルです。
- 仕上げ工程前に、CBN 工具にて中仕上げを行います。前加工にて取り代の均一化することが、仕上げ工程での結果に大きく影響します。
- PCDRB can realize mirror like finishing on full surface machining and achieve the sub-micro level surface roughness, even for approx. 39hrs finishing process.
- Before finishing, use CBN to process semi-finishing. Leaving constant stock amount on semi-finished surface will have great affects in the finishing process.

Example of a mold insert in ELMAX 60HRc
Process time : more than 50 hours (NS Tools)

Micromilling process

Micromilling is widely used for fabrication of grooves, cavities and 3D concave/convex shapes

A lot of manufacturing processes (MEMS technologies for example) lack the ability to make 3D structures from some materials (silicon, polymer resins)

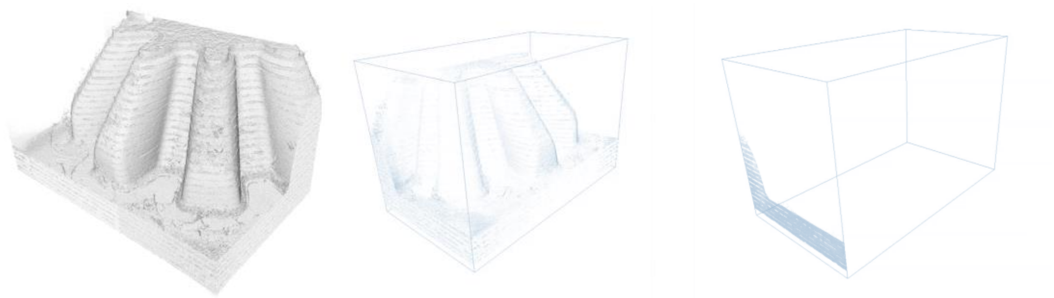
They are not suitable to produce 3D complex geometries for small and medium lot sizes

Micromilling is one of the most promising approach to overcome some of the limitations of common micromanufacturing techniques

Micromilling is not limited in terms of materials to machine (ferrous, non ferrous, hard, brittle, polymers, ceramic, …)

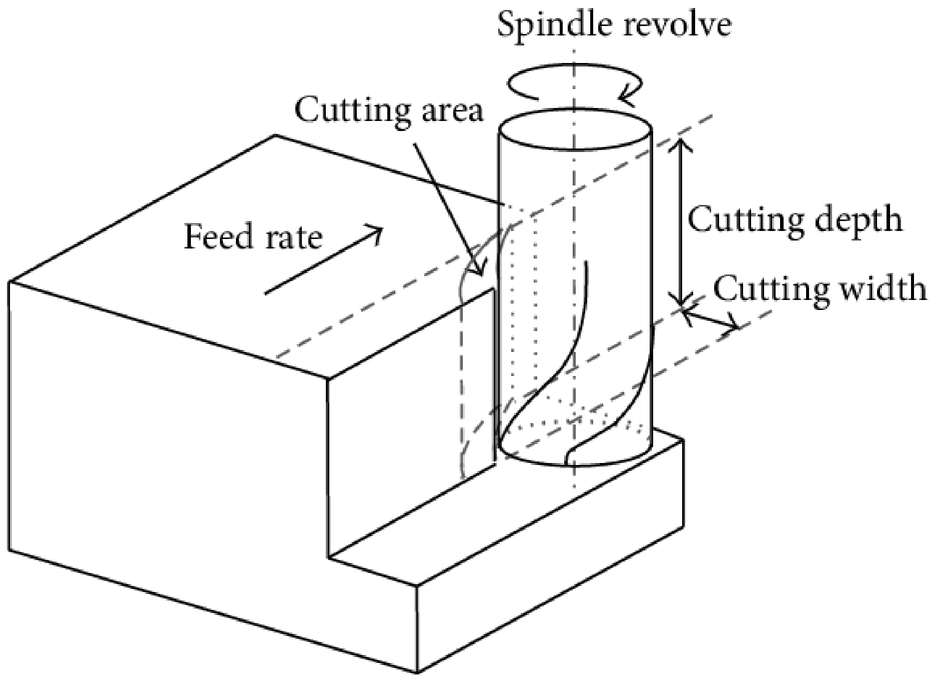
Example : micromilling of a 2mm thick paper sheet
S. Thibaud – 2019

Nano-tomography by CT Scan (MIFHySTO)



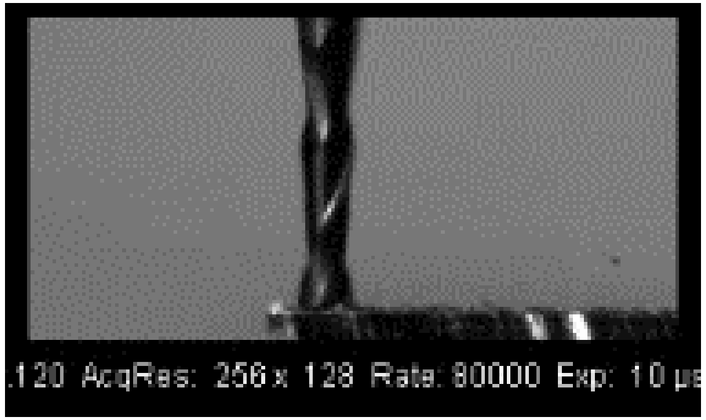
Micromilling process

Milling at micro-scale



Spindle Rate (Theoriticaly) : N=76400 rpm
Spindle Rate (Really) : N=36000 rpm

Feedrate : Vf=305 mm/min



High Speed Imaging of a milling operation (surfacing)
Tool diameter : 0.5 mm – Tool material : WC-Co
Material : AISI316L – 80000 fps

Cutting depth = 20 µm
Cutting width = Tool Diameter

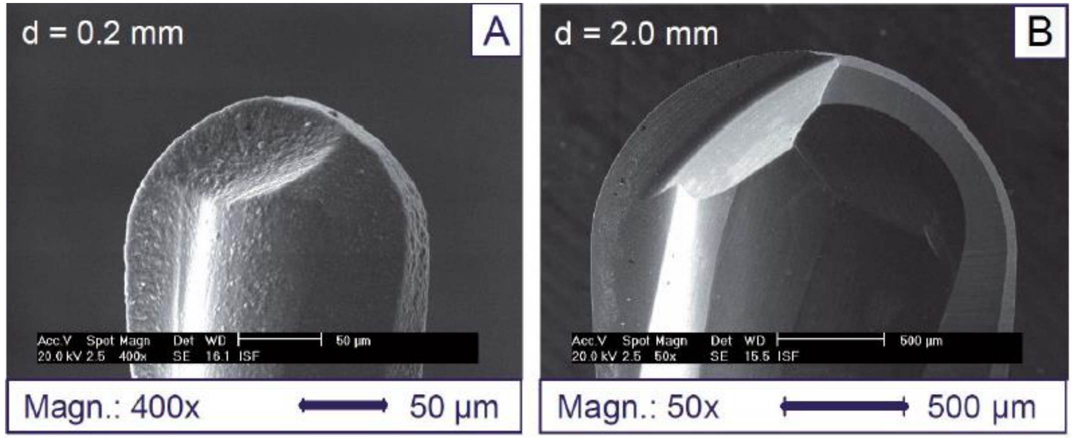
High spindle rate
Low feedrate
Low Cutting Depth
Material Removal rate is very low
≠
High Speed Machining
(High Cutting Speed and High Volume of removal material)

Process time is soon important and it is difficult to know if the tool is still in operation

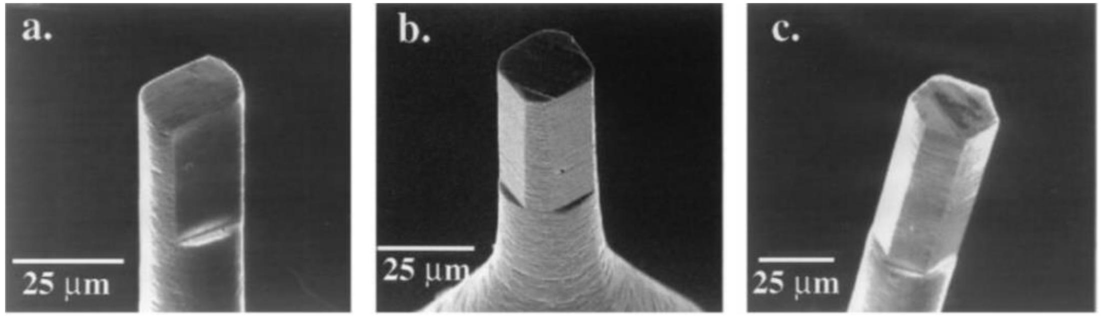
Micromilling process

Milling at micro-scale : a simple downscaling consideration ?

Microtools



Differences between two end ball mill
(with a ratio of 10) – Adams et al. (2001)



Others designs obtained by Focussed Ion Beam Technology
Dornfeld et al. (2006)

Texture / edge sharpness / Achievable Geometries

Micromilling process

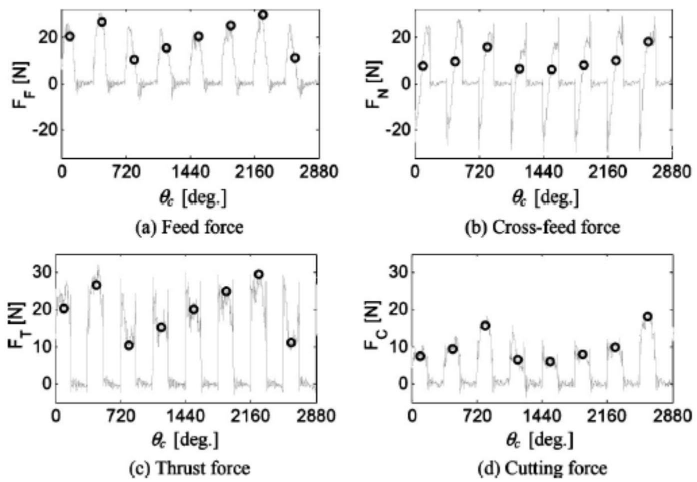
Milling at micro-scale : a simple downscaling consideration ?

Microtools

In micromilling, tool length (active parts) is often much greater than the tool diameter $\frac{l}{d} \sim 1$ to 20

Microtools are not rigid : tool bending during process

Deflection f is proportional to the inverse of the moment of inertia I



Effects of tool bending on cutting forces
Kim et al. (2004)

$$f \sim \frac{L^3}{E d^4}$$

$d \searrow \quad f \nearrow\nearrow\nearrow\nearrow$

Cutting forces are proportional to the cutting area A

$$F = KA \sim Kd^2 \quad d \searrow \quad F \nearrow\nearrow$$

K : Specific force coefficient

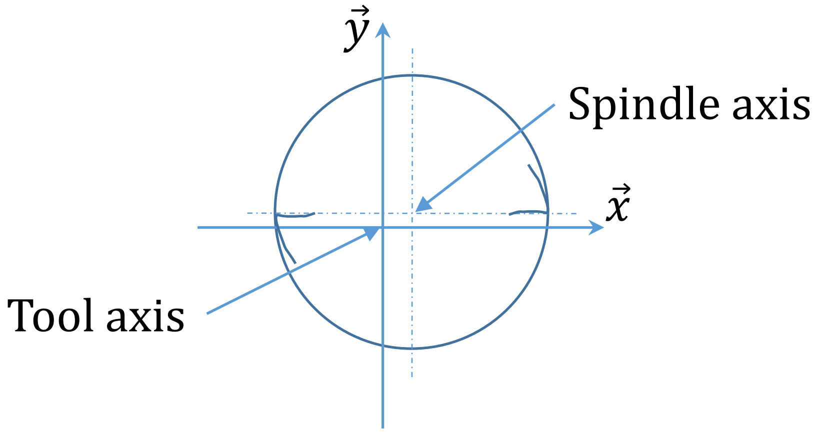
Leads to
- an increase of cutting force,
- Imbalance of force evolution,
- Unstable cutting conditions
- Tool breakage,
- Shape errors ,
- Poor surface quality

Micromilling process

Milling at micro-scale : a simple downscaling consideration ?

Microtools

Microtools axis are not perfectly aligned with spindle axis : run-out phenomena (axial and radial)



Run-out lead to

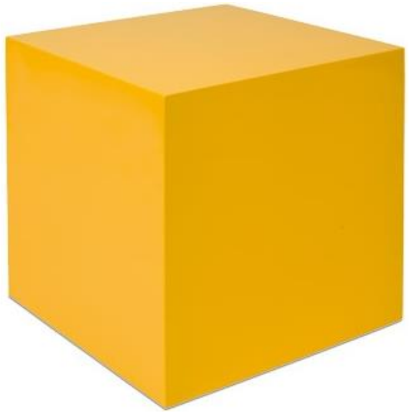
- Cutting asymmetry (imbalance forces)
- An increase of the (real) tool diameter nor tool length

Microtools are not perfect : unbalance phenomenon
During process, dynamic phenomena lead to axial and radial defects (axial variation, dynamic bending)

Micromilling process

Milling at micro-scale : a simple downscaling consideration ?

Scale effects



Surface/volume ratio = S/V=1/a

If a<1 -> Surface effects are more important than volume effects

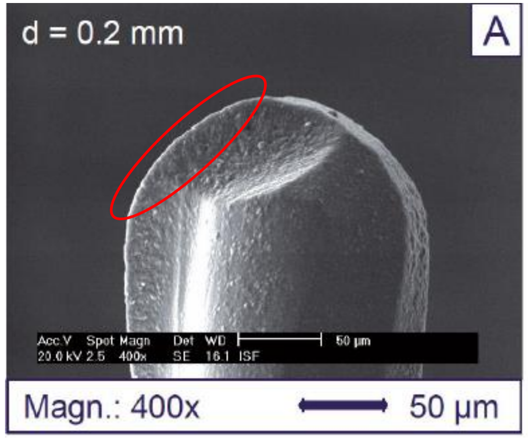
If a>1 -> Volume effects are more important than surface effects

	Macro (Ø=D>1)	Micro (Ø=d<1)
Cutting rate	Vc	Vc
Spindle rate N	~Vc/D	~Vc/d
Feed per tooth fz	~D	~d
Feed rate Vf	=fz.Z.N~Vc	~Vc
Cutting depth ap	~D	~d
Cutting width ae	~D	~d
Cutting force	$\sim D^2$	$\sim d^2$
Chip volume rate Q	$=Vf.ap.ae\sim D^2$	$\sim d^2$
Cutting power P	$\sim Vc.D^2$	$\sim Vc.d^2$

Micromilling process

Milling at micro-scale : a simple downscaling consideration ?

The Sharpness edge radius & Material Microstructure



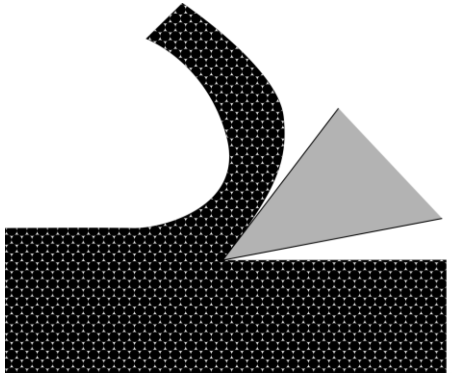
The cutting edge can’t be assumed to be perfectly sharp : a fillet appears

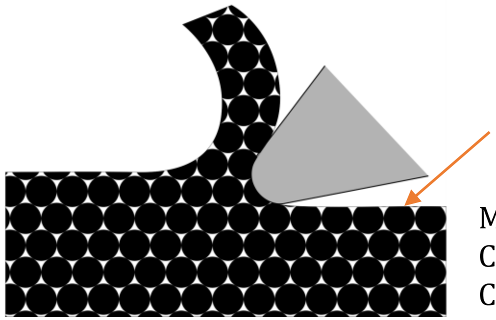
This fillet is named sharpness edge radius

During the machining operation, this radius is of the same order of magnitude as the cutting depth

The process is not a perfect cutting operation and a ploughing phenomenon is observed (plastic deformation)

Macro : sharp edge
Cutting depth >> Material grain size
Cutting process





Hardened surface

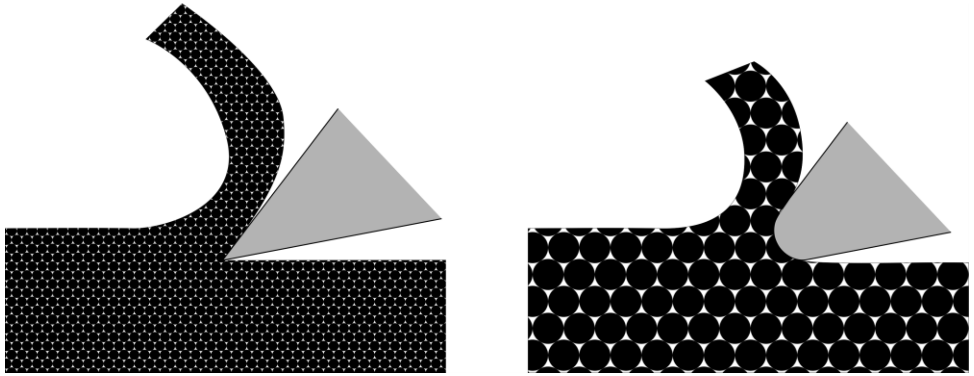
Macro : fillet edge
Cutting depth ~ Material grain size
Cutting process + ploughing

The sharpness edge radius is tough to measure where it is one of the most important parameter

Micromilling process

Milling at micro-scale : a simple downscaling consideration ?

Scale effects : influence of material microstructure



As define previously, one of scale effects due to downscaling is associated to the material microstructure

Geometrical or process parameters are of the same order of magnitude

Material behavior and cutting operations are quite dependant of this characteristic length

Micromilling process

Milling at micro-scale : a simple downscaling consideration ?

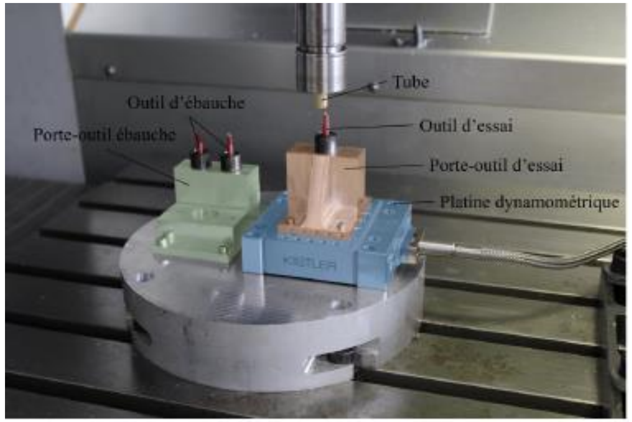
Others parameters

- Rigidity, dynamic and thermal expansion of the machine-tool
- Machine repeatability (few or less than the micrometer) and precision (few or less than the micrometer)
- Machine interpolation
- Spindle rate limits (on the market : limits to 100000 rpm with low torque – classicaly 24000 rpm to 70000 rpm)
- Toolpath (path smoothing, interpolation, CAD model discretisation)
- CAD Model (meshing, …)
- Lubricant
- Tool material
- Coating
- …

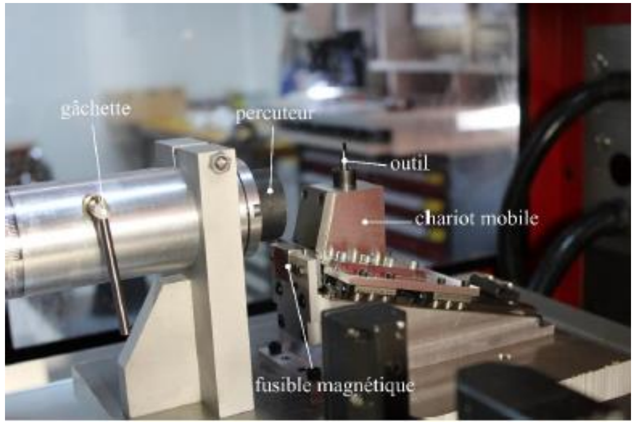
Micromilling process

Milling at micro-scale : a lot of information are available in the chip (thermal, mechanical, chemical evolutions)

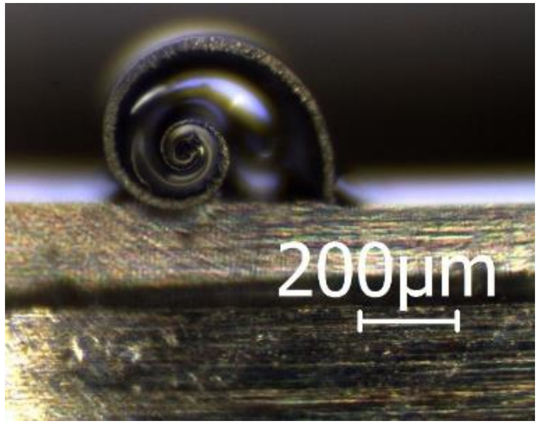
- Special tests are necessary to obtain a representative chip : quick stop test
- Micro-turning of a chip on a tube with a turning tool equivalent (in terms of cutting angle) to the milling tool



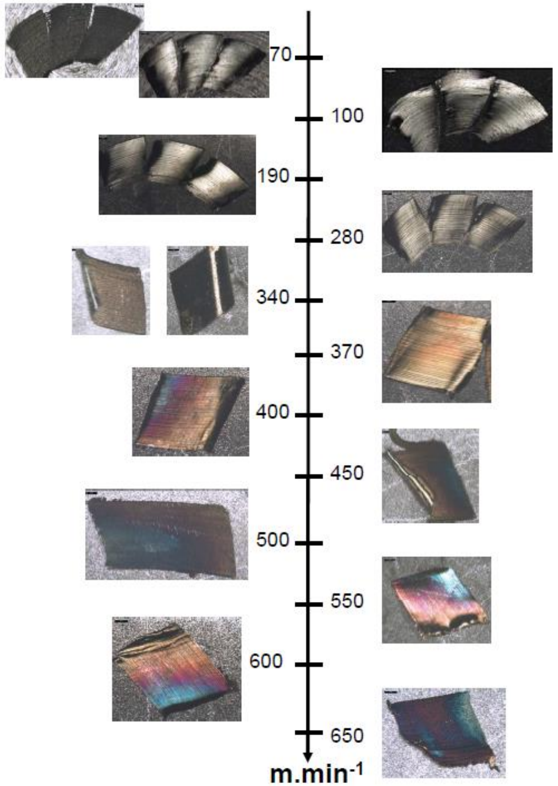
Cutting forces measurements with a 4-axis dynamometer (Kistler)



Micro Quick Stop Test (R. Piquard Phd Thesis)



Chip obtained by Micro Quick Stop test



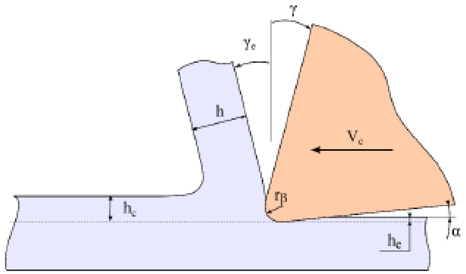
Evolution of the chip morphology with respect to the cutting speed – A. Maurel PhD Thesis (2009)

- On the chip : Metallurgical analysis (material transformation, crystal orientation,), shape and mechanical analysis (nano-hardness)
- + 4 axis forces (3 linear forces and axial torque)

Micromilling process

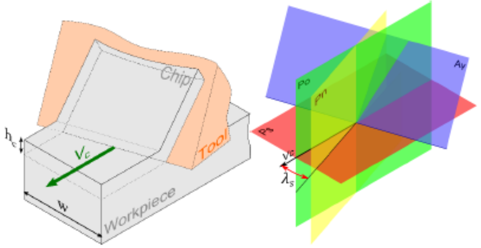
Milling at micro-scale : numerical and analytical modeling to understand and optimize the process

First approach : analytical modeling



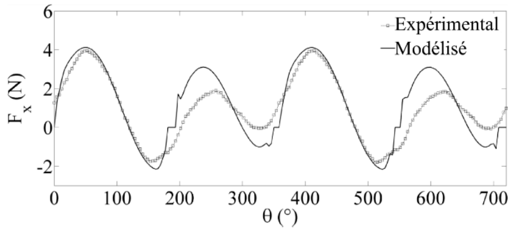
It consists in :

- Discretizing the cutting and the geometrical definition of the tool
- Integrating the mechanical behavior of the milled material (elastic-plastic model at high strain rate and high strain level with thermal effects)
- Comparing **global results** (forces) after integration for a **chosen configuration**

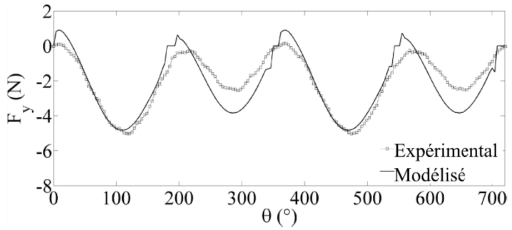


+ Very fast computational time : parametric studies for process optimization or sensitivity analysis are available

- Only global results and no information on the material

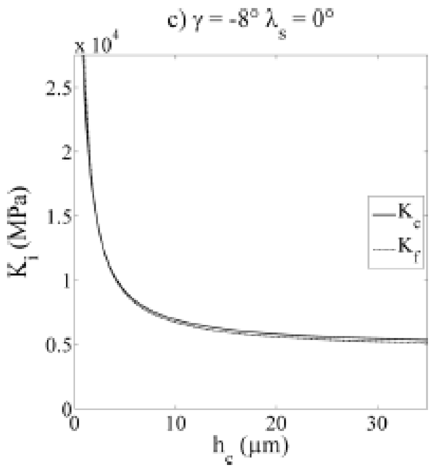


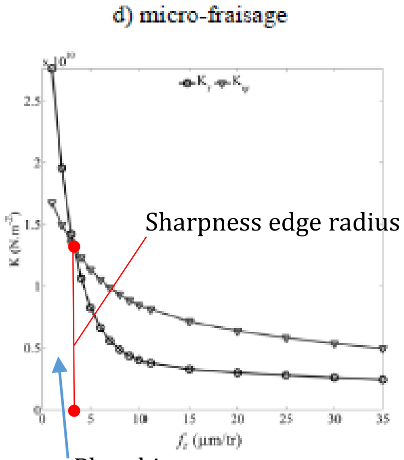
Spindle Angular position



Spindle Angular position

R. Piquard, Phd Thesis, Analytical model by considering run-out and flexible tool





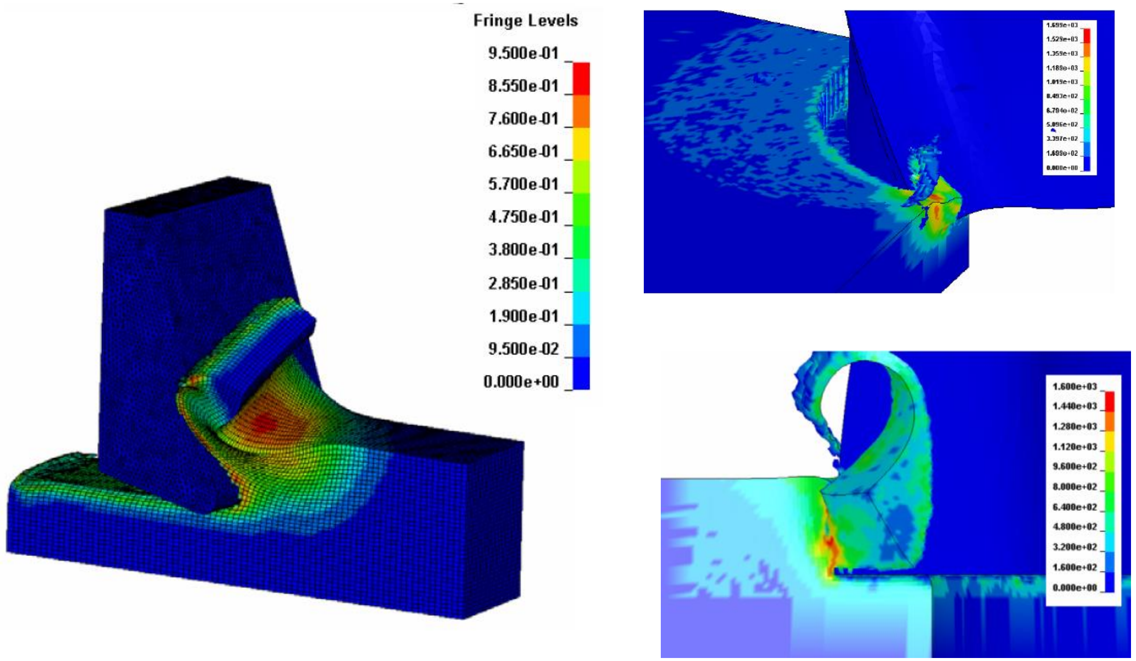
A. Maurel-Pantel, PhD Thesis

Micromilling process

Milling at micro-scale : numerical and analytical modeling to understand and optimize the process

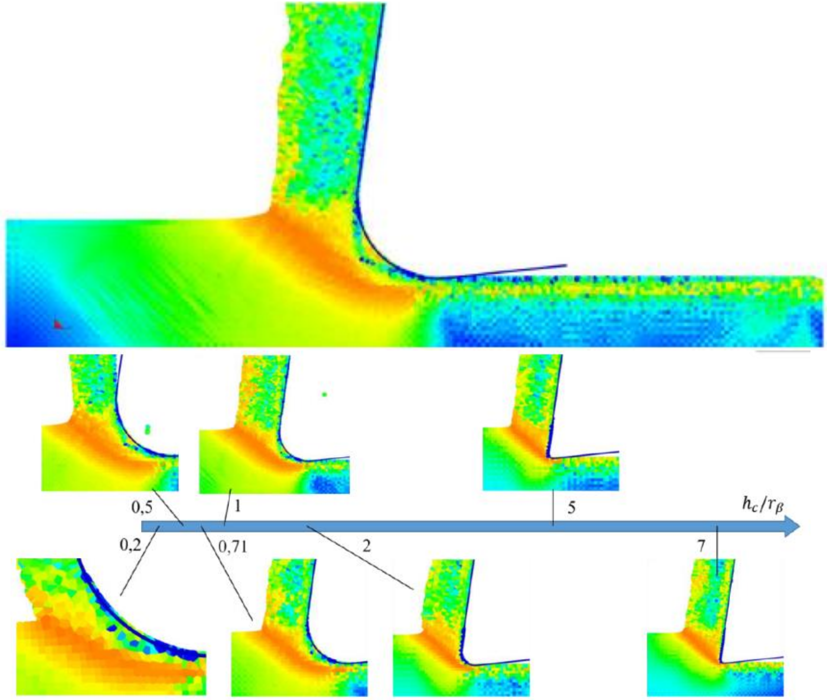
Second approach : numerical modeling

Finite element simulations



A. Maurel, Phd Thesis, FEM of turning/milling processes

Finite element / Meshless method simulations



R. Piquard, Phd Thesis, FEM/SPH Method to simulate micromilling

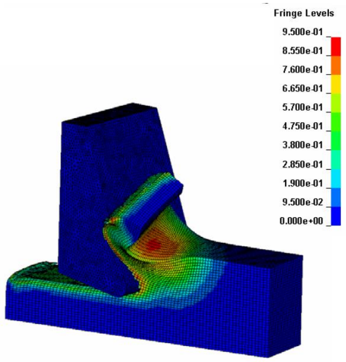
Traditional micromachining

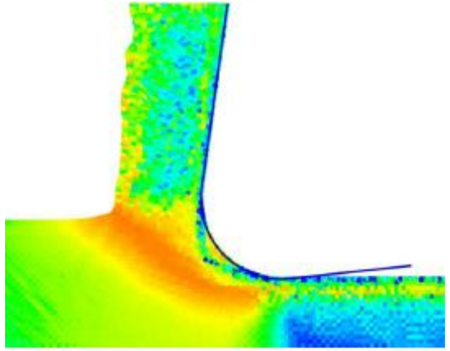
Micromilling process

Milling at micro-scale : numerical and analytical modeling to understand and optimize the process

Second approach : numerical modeling

FEM/SPH methods

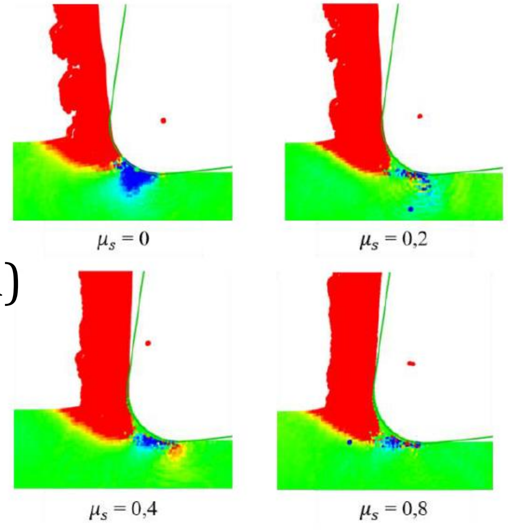


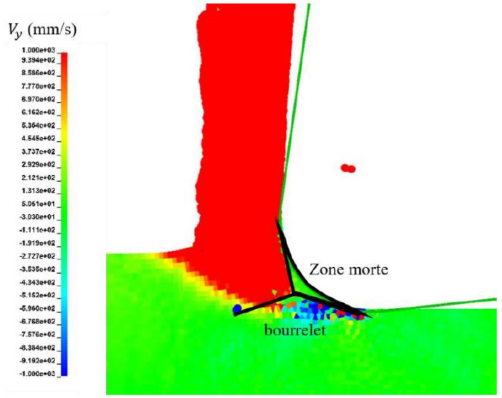


It consists in :

- Decomposing (meshing) the different domains
- Defining interaction between parts (contact / friction)
- Introducing the complex material behavior (mechanical / thermal)
- Solving the dynamic laws (explicit dynamic model)
- Post-processing results

+/- Contact/Friction (difficulties to modelize surface interaction)
+ Local approach and analyzes
- Model size (more than 100000 dofs - >1To datas)
- Time processing (more than 4 days with a MPP clusters)
+ In principle we can use sensitivity analysis or optimization but in practice (time processing) …
- Limits in terms of total tool displacement (time processing)





Conclusions

- Micromilling and micro-turning are note a simple downsizing of the macro one
- Micromilling and micro-turning are one of the more important technologies to obtain 3D comple shapes in various materials
- Taking into account scale effects are essential
- It is not possible to use the same approaches than at macro scale
- Numerical and analytical modeling coupled with experiments helps to understand phenomenon and also to optimize processes
- Actual challenges are based on increase productivity by process hard materials

The smallest micromanufactured soccer ball in the world (32 parts)
S. Thibaud – ENSMM - 2019

µRubik's cube – Smallest rubik's cube in the world
9 mm length
Terminal year ENSMM
S. Thibaud 2019

Towards very hard material milling

Towards very hard material milling

Time-Frequency Dpt – ACEPI Group

Micromachining

Advanced Removal Processes

Micromachining

Advanced micro-machining are base on special processes that are not associated to traditional micromachining processes : everything else !!!

Some of them are especially developped for micromanufacturing

For this lecture, we focus on

- Ultrasonics machining
- Electrical-Discharge machining (EDM)

Time-Frequency Dpt – ACEPI Group

Ultrasonic Vibration Machining

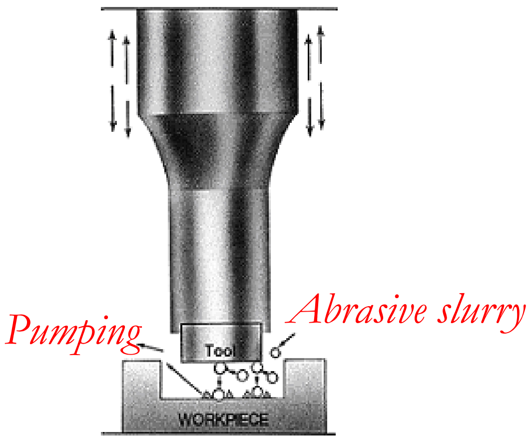
Advanced Removal Processes

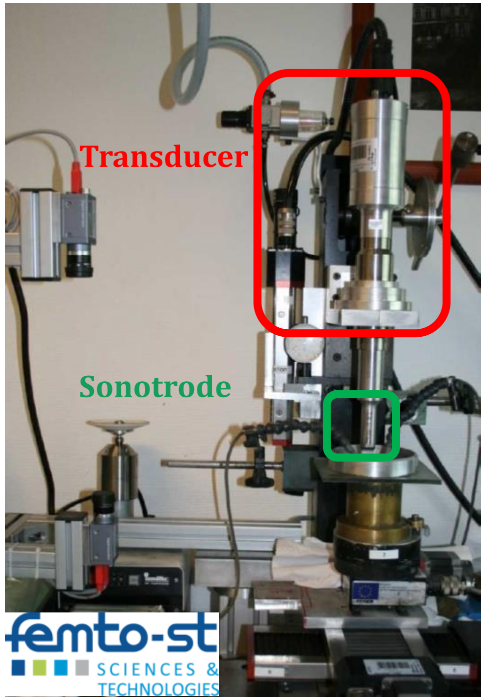
Micromachining : ultrasonic vibration machining

Ultrasonic vibration machining is a subtrative manufacturing process by using high frequency and low amplitude vibration of a tool in front of the surface with fine abrasive particles

The tool move in direction (axial or radial position) of the surface with low displacements (few microns to few 100µm)

Frequency ~20 kHz





Frequency-Time Dpt - ACEPI Group

USM consists of two major components :

- A transducer : it converts oscillating current to a mechanical vibration (from 18 to 40 kHz)
- A sonotrode = the tool representing the negative shape of the cutting shape to fabricate

Two technologies are used for transducer

- Magnetostrictive transducer
- Piezoelectric transducer

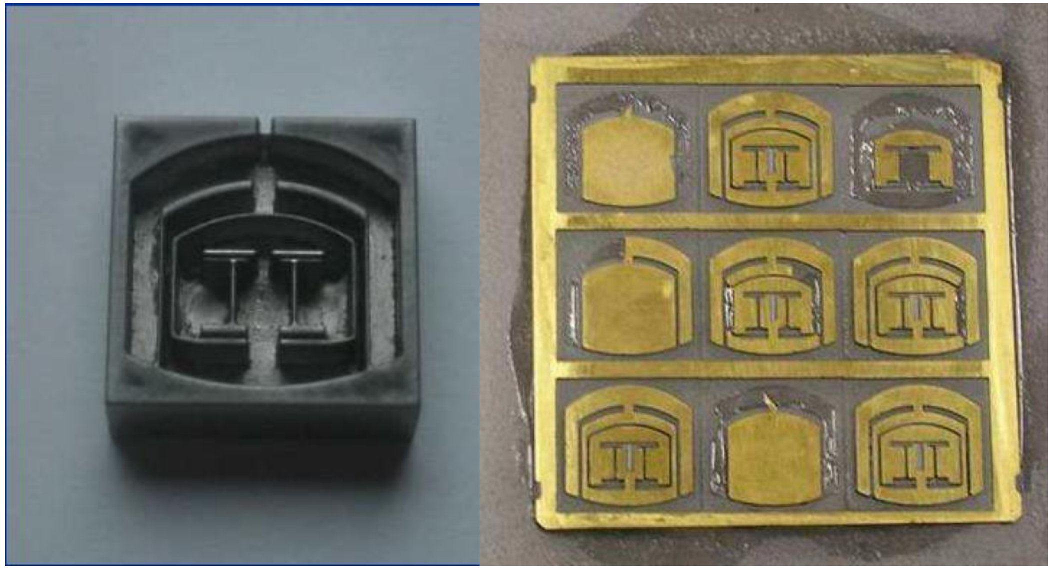
Transduce vibrates the sonotrode at low amplitude and high frequencies

Micromachining : ultrasonic vibration machining

Sonotrode is usually made of low carbon steel

A constant stream of abrasive slurry flows between workpiece and the sonotrode (pumping)

This stream allows to flow away debris and micro-chips from the cutting area



Accelerometers – (Sonotrode and parts) Frequency-Time Dpt - ACEPI Group

Different slurries are used

- boron carbide
- Aluminum oxide
- Silicon carbide

in a suspension of water solution (from 20% to 60% by volume)

The sonotrode removes materials from the workpiece by abrasion

The results is a perfect negative of the sonotrode's shape

USM allows very complex features with very high precision

It depends on the sonotrode's precision (micromilling)

Micromachining : ultrasonic vibration machining

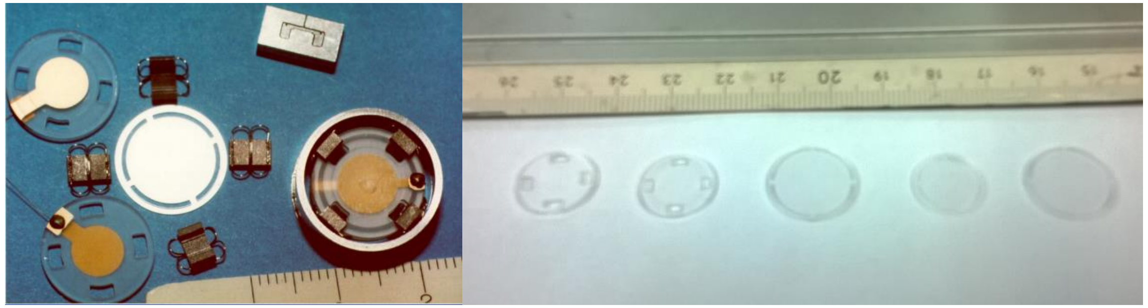
Machining time depends of the physical properties of the workpiece’s material :

- Hardness
- Porosity
- Fracture toughness

The inclusion of microcracks and microcavities features on the materials surface depend highly on the **crystallographic orientation** and the materials **fracture toughness**.

USM is a key technology to machine brittle and hard materials like crystals (Si, Quartz, Sapphyre,GaPo4, Ceramic, …)

Minimum hardness : >45 HRc



BVA resonators – ACEPI Group

Watch Component

Micromachining : ultrasonic vibration machining

Other techniques

- Rotary ultrasonic vibration machining (RUSM) : the sonotrode is able to revolve about the vertical axis.
    - The abrasive slurry is replaced by a diamond coating on the sonotrode working area
    - RUSM is well suited in machining ceramics, glass, quartz, titanium alloys, alumina and silicon carbid
    - Application to micro-drilling is quite promising
- Chemical-assisted ultrasonic machining (CUSM)
    - A chemically reactive fluid is used machining of glass and ceramics materials
    - Improvement of material removal rate **and** surface quality by using hydrofluoric acid

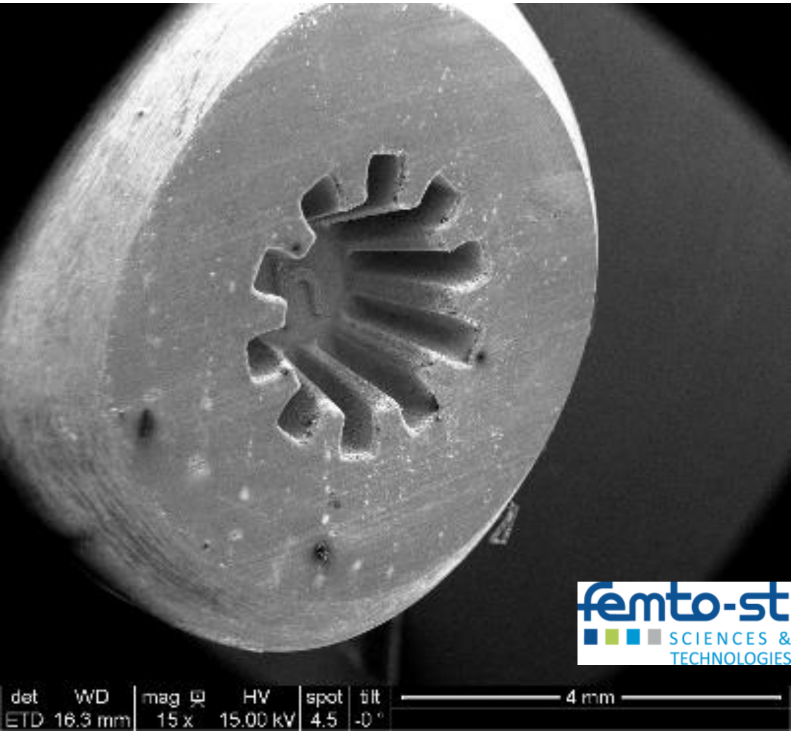
Micromachining : ultrasonic vibration machining

Advantages

- Fabrication of complex features
- Application to hard and brittle materials **and** non conductive materials (electrical conductivity)
- High tolerances can be achieved
- Uniformity of the surface properties obtained by USM

Disadvantages

- Driven by microchipping or erosion mechanisms :
    - material removal rate (MRR) is very low
    - Processing time is long (very long)
- Micro-drilling can be difficult in relation with abrasive flow in the cavity
- USM can only be used on materials with a high hardness value (more than 45HRc)



M. Personeni / S. Thibaud – FEMTO-ST - 2019

µElectrical-Discharge Machining

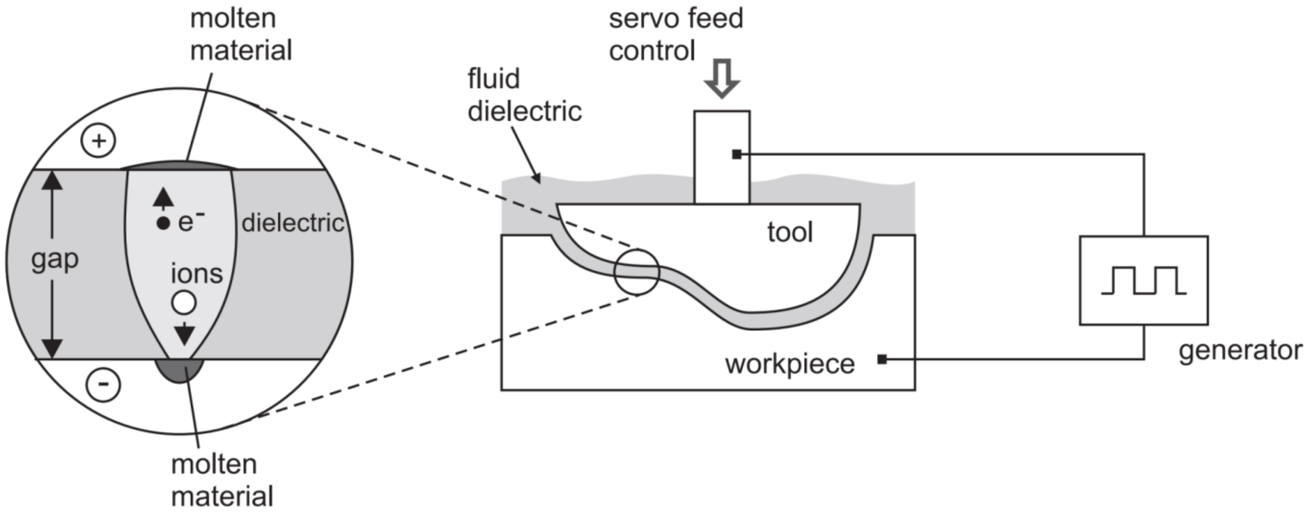
Advanced Removal Processes

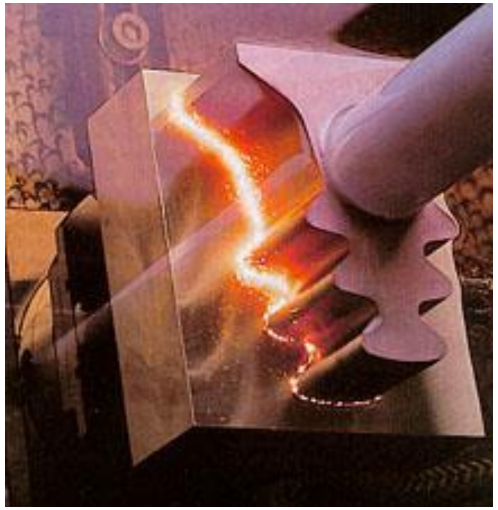
Micromachining : μEDM

Micromanufacturing processes based on the machining of conductive (electrical) material by using electrical discharges (sparkles)

Electrical discharge machining = Spark machining

Material is removed from the workpiece by a series of current discharges at high frequencies (kHz at MHz) between to electrodes (the part and the tool) separated by a dielectric liquid under an electric voltage





Micromachining : µEDM

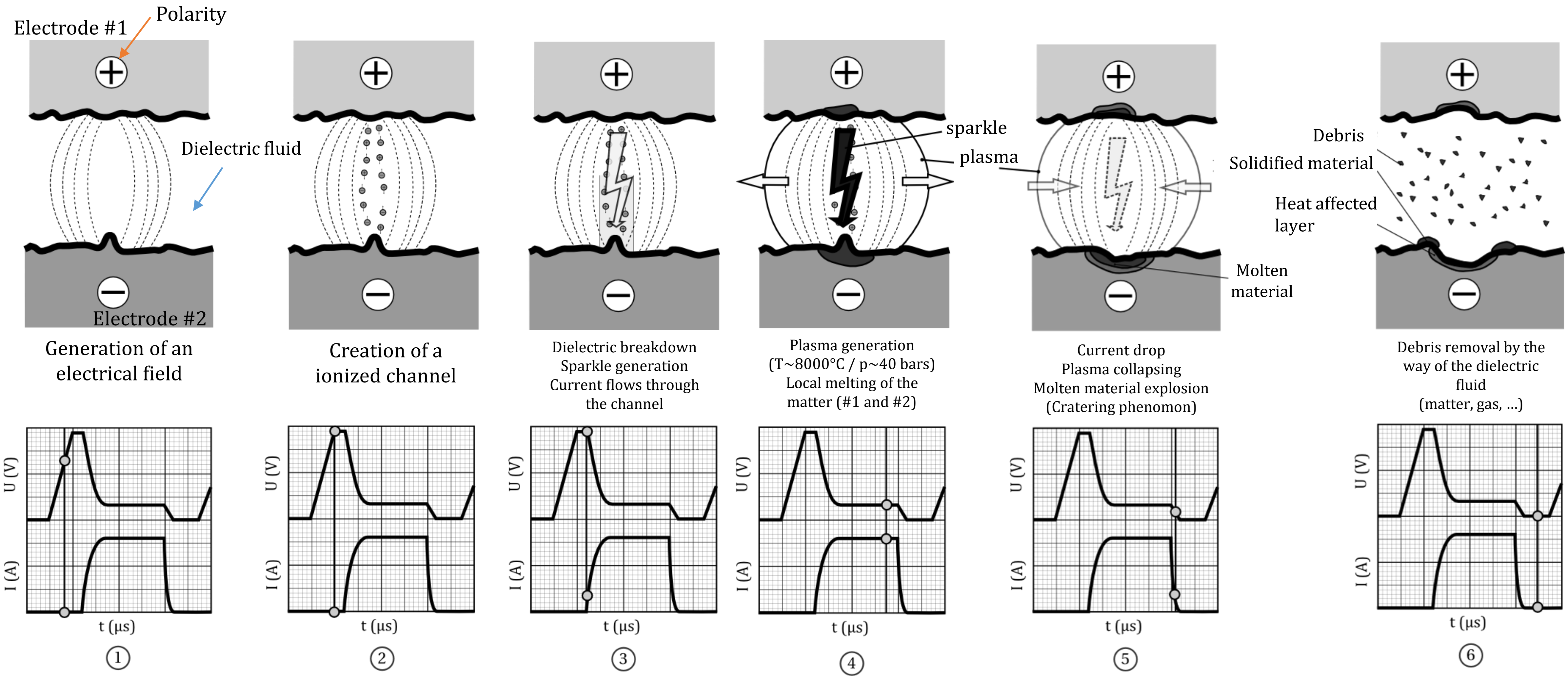
No physical contact between the two electrodes

The workpiece and the tool (electrode) wear out during the process

Currently, the tool wears out faster than the workpiece : a wear monitoring is necessary

Micromachining : µEDM

Principle



Micromachining : µEDM

Main advantage

Machining or micromachining of material independently of its hardness

In principle, only conductive materials can be machined …

Some studies (Shabgard and Khosrozadeh, Mai and al) use NTC to activate sparkles on the workpiece surface

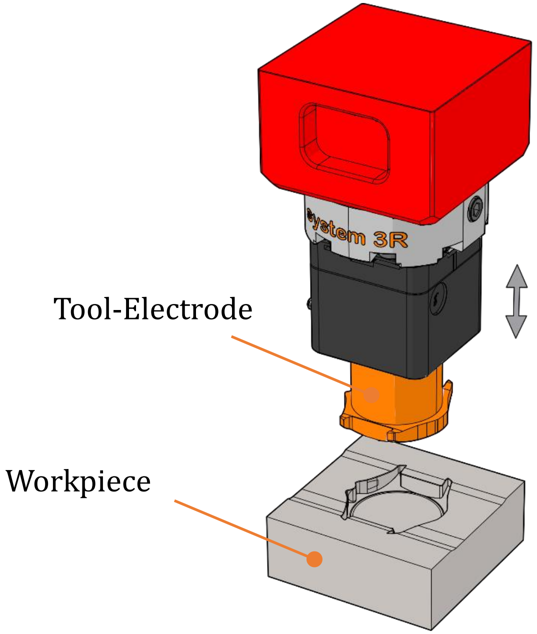
Electrical discharge machining is a key technology to fabricate mold and tools

Electrodes

The tool (electrode) is obtained classicaly from electrolytical copper (very high conductivity), tungsten-carbide and Graphite

In die sinking process

Electrode are obtained by (micro-)milling and turning and potentialy by an another EDM processes (WEDM)



Die Sinking

Jiangsu corp

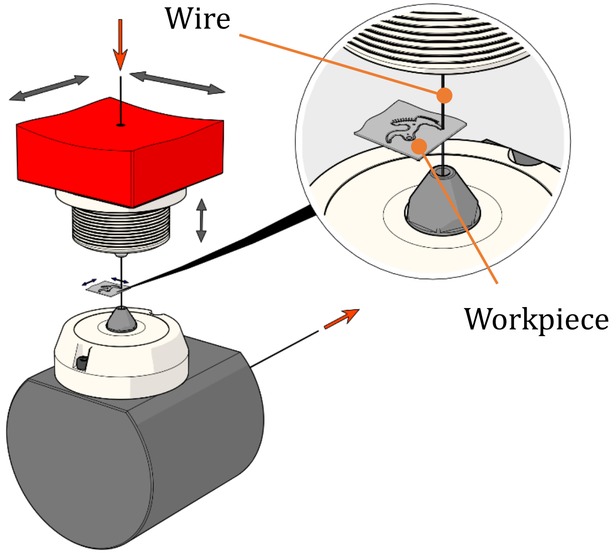
Micromachining : µEDM

Electrodes

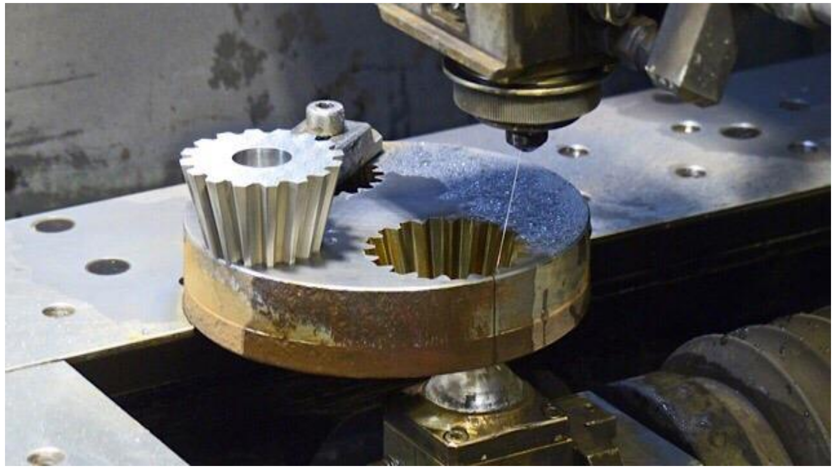
In wire electrical discharge machining

the electrode is replaced by continuously unwound wire : 2 to 4 axes micro-milling

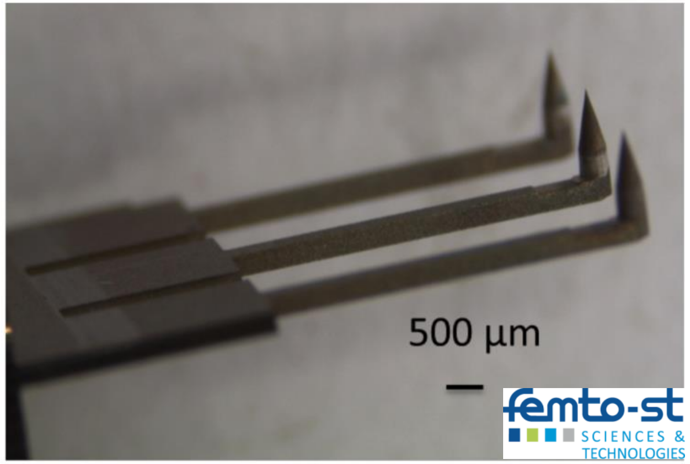
In micro-WEDM, the wire diameter is in the range 20 µm to 300µm



Wire EDM



4 axis WEDM application – WayKen Rapid Manufacturing



Dynamic tip microscopy in Tungsten-Carbid – MIFHySTO WEDM / MicroEDM Milling (Chain processing)

Electrodes

In micro-milling

Electrodes : Hollow or solid rod bar are used

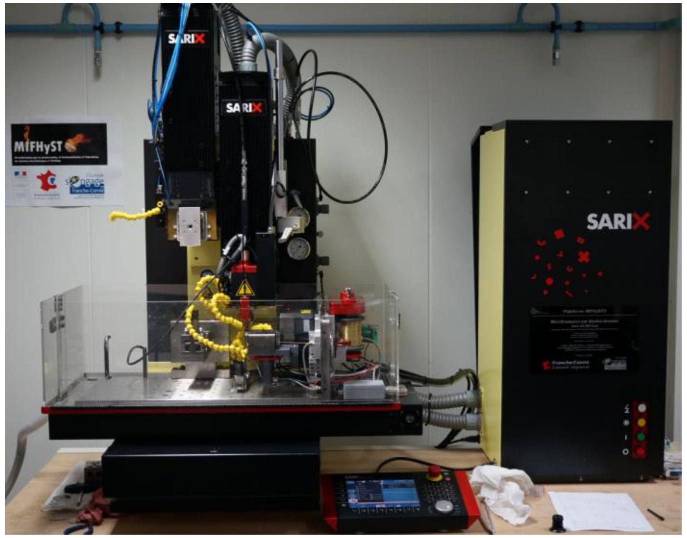
It can be used as a drill or a mill

The rod diameter can be ajusted by WEDM

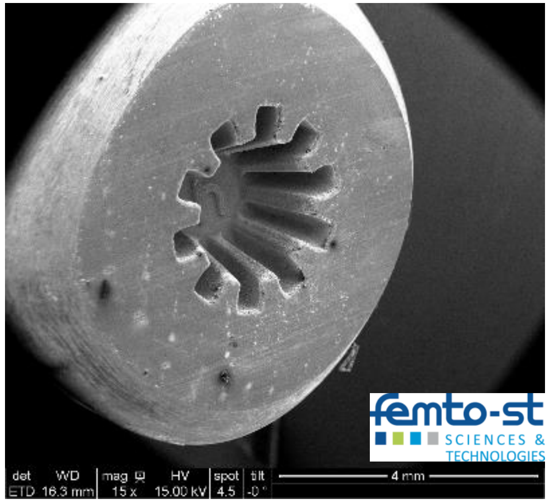
Up to 20 µm diameter

Milling of very small features

MRR is very low … time processing can be very expensive



µEDM Milling Machine SARIX SX 200 Dual
MIFHySTO - 2011



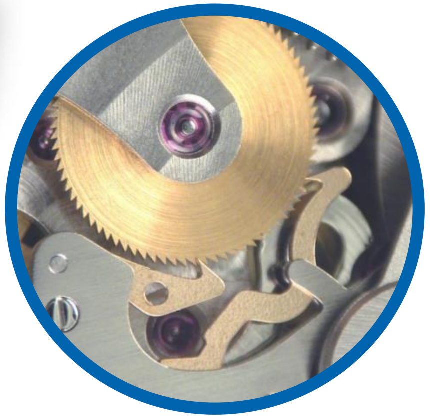
Net Shape forging mold in WC-Co obtained by
µEDM Milling – Edges radii = 10µm
MIFHySTO – 2015 – Time processing : **150 hours**

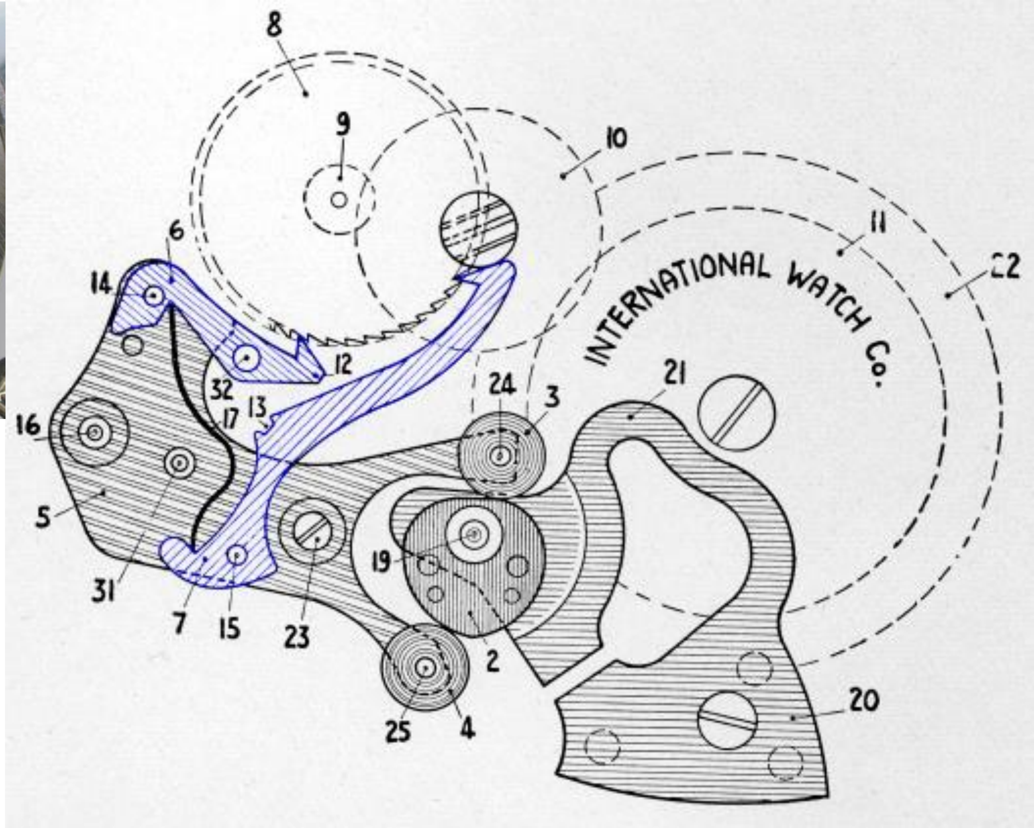
Micromachining : µEDM

Application of µEDM in industry and scientific developments

Is it possible to fabricate high precision watch component in advanced (conductive) ceramic ?

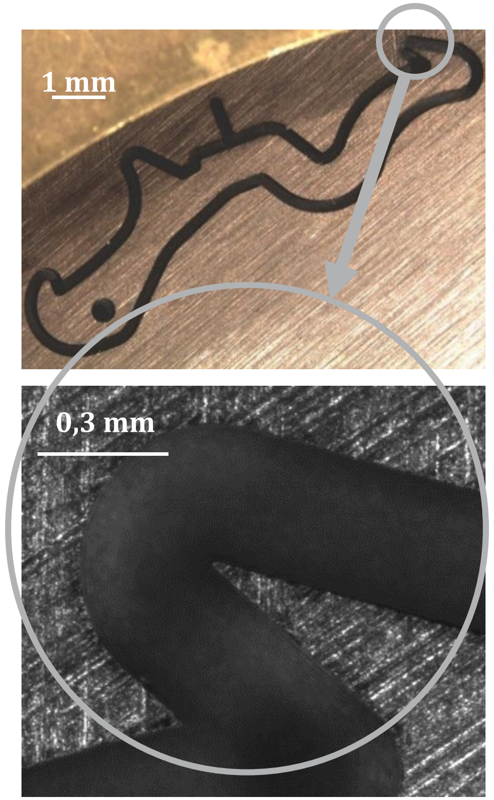
IWC Schaffhausen





Application of µEDM in industry and scientific developments

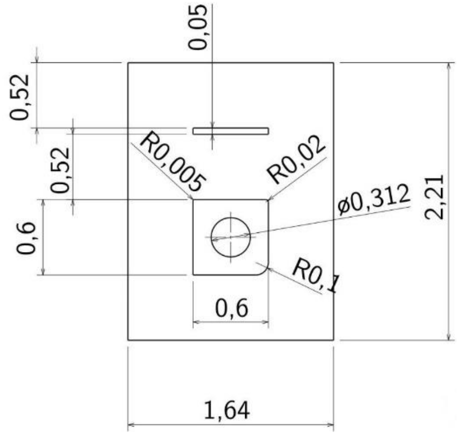
Is it possible to fabricate high precision watch component in advanced (conductive) ceramic ?



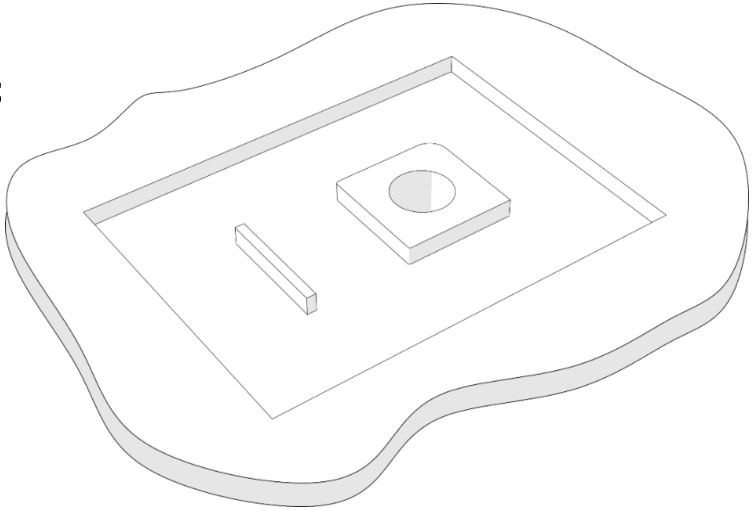
Proof of concept Ok but … time processing = 18 hours !!!

Technological development + Scientific approaches

As processing time can be very expensive, experimental testing have to be adapted



Definition of representative features
- Pocket
- Thin wall structures
- Hole
- Fillet edges



Electrode type : A 300 µm diameter hollow rod (60µm diameter hole) in WC-Co

Influence of process parameters

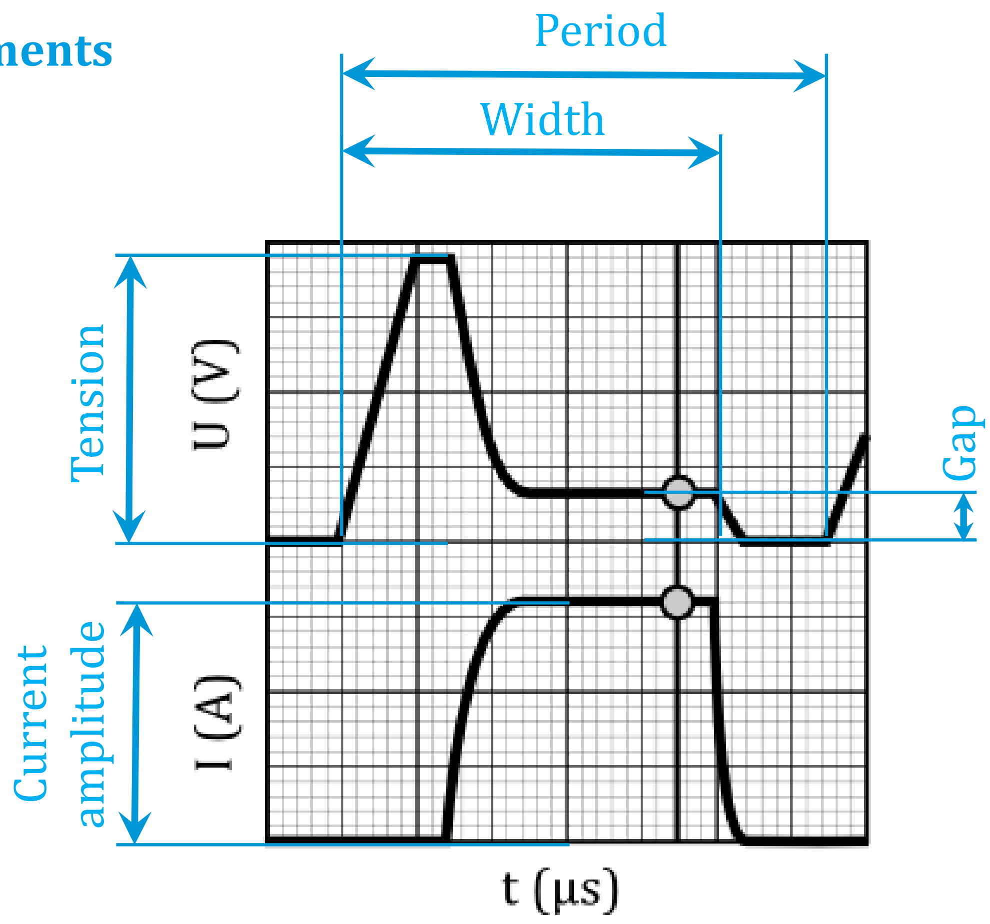
How to optimize EDM process experimentaly ? **A design of experiments**

Tested parameters (generator parameters)

- Tension
- Gap
- Width
- Frequency
- Current amplitude

Fixed parameters

- Electrode : negative polarity
- Spindle speed
- Generator Gain
- Dielectric
- Generator type

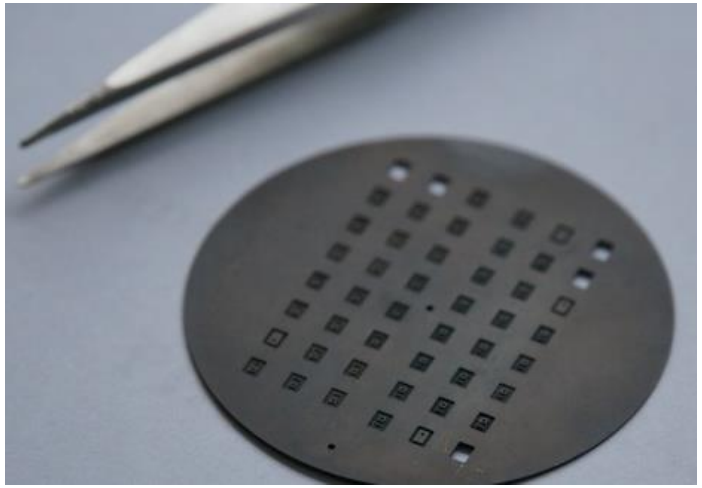


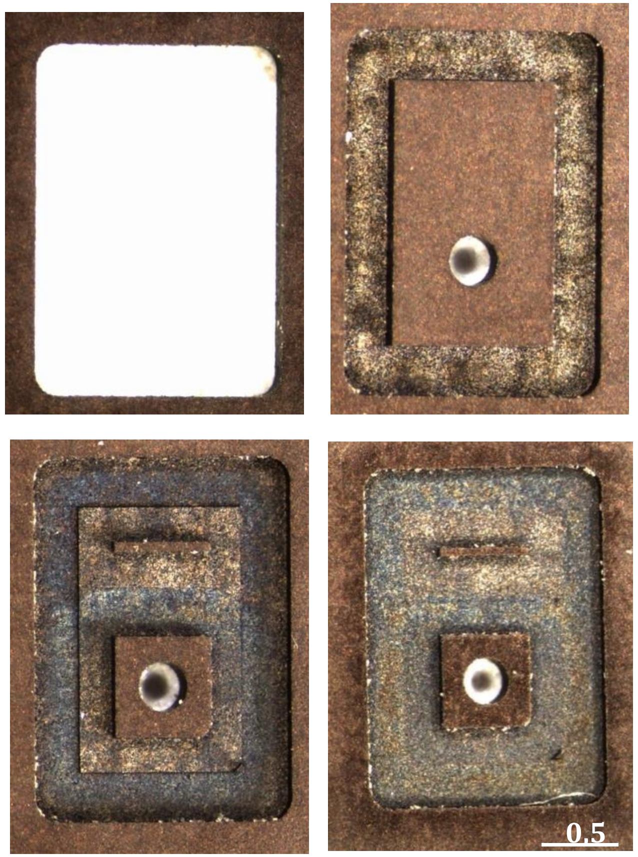
Influence of process parameters

48 experiments = 250 hours for processing time and 75 hours for geometrical measurements !!!

Results

- More than 325 hours !!!
- Repeatability problems due to the material (phase disparity)
- Machine control
- Tool wear (more than 600%)



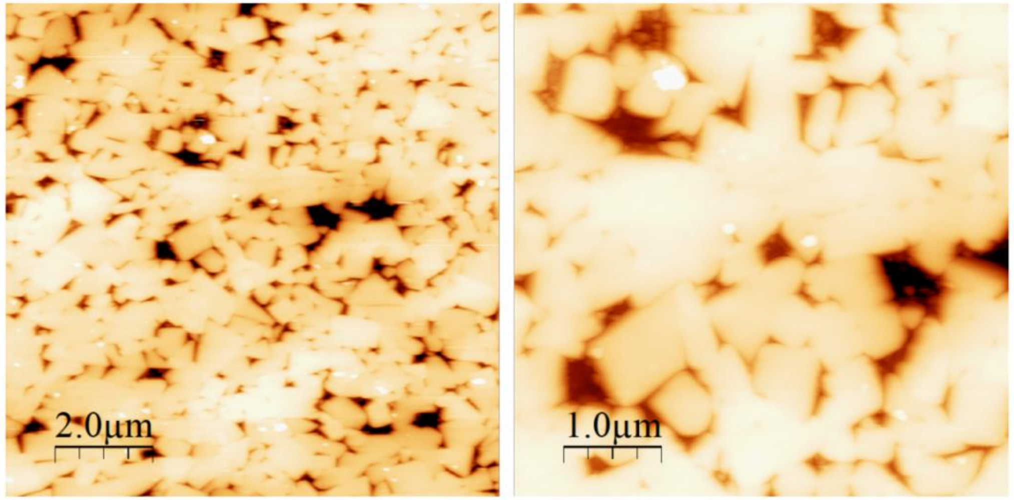


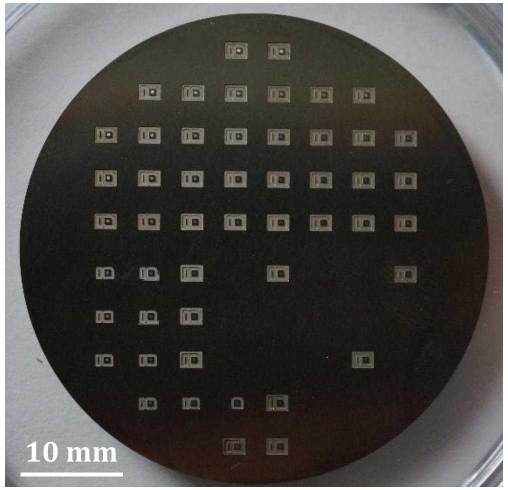
Due to repeatability problems : material is changed by WC-Co

Micromachining : µEDM

Tungsten Carbide

- Tungsten Carbide with Cobalt matrix (10%)
- Grain size = 0,6 µm
- High wear resistance
- High electrical conductivity
- High toughness resistance





Time processing : 100 hours
Surface and Geometrical characterisation : 50 hours
Repeatability is excellent

At this scale, material is the more important factor to consider !!!

Micromachining : µEDM

By considering the DOE's results, we can optimize electrical parameters to

- Increase the Material Removal Rate (decrease time processing)
- Improve surface quality
- Control geometrical defects
- Control tool wear : **it's the most critical factor to control in µEDM**

Recent works (Ramasso and Thibaud, 2019) : Listening to the evolution of the process by the way of the workpiece and by acoustic emission

Deep Learning + Artificial Intelligence (realtime) + Acoustic Emission + µEDM = smart micro-manufacturing

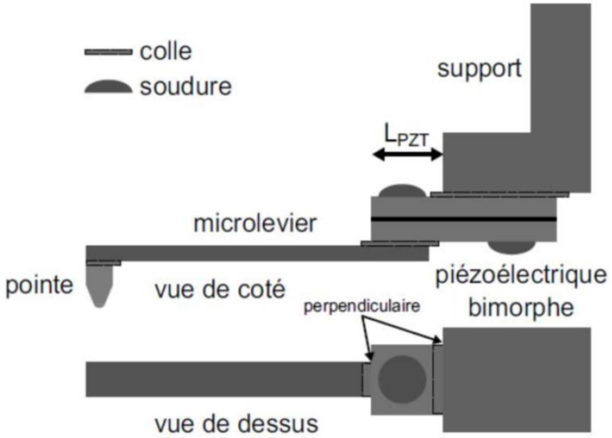
At this scale, material is the more important factor to consider !!!

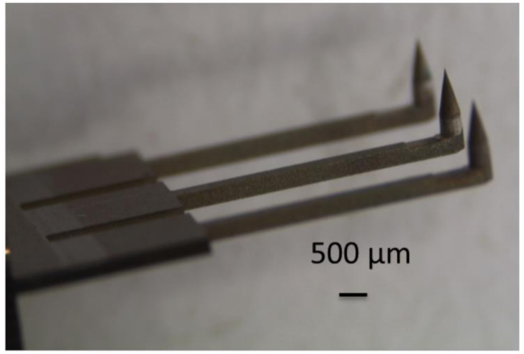
It is then necessary to finely characterize the material behavior at the microscale as close as possible to the conditions of use and production

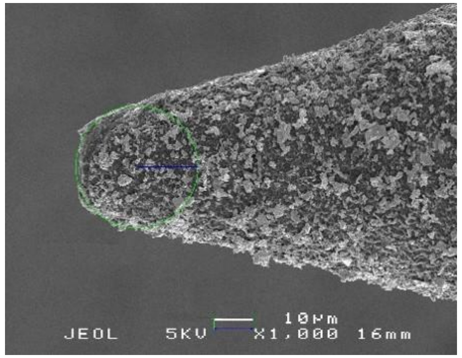
Micromachining : µEDM

Example : a dynamical tip for microscopy – FEMTO-ST – Micro-Nano Sciences Dept / MIFHySTP

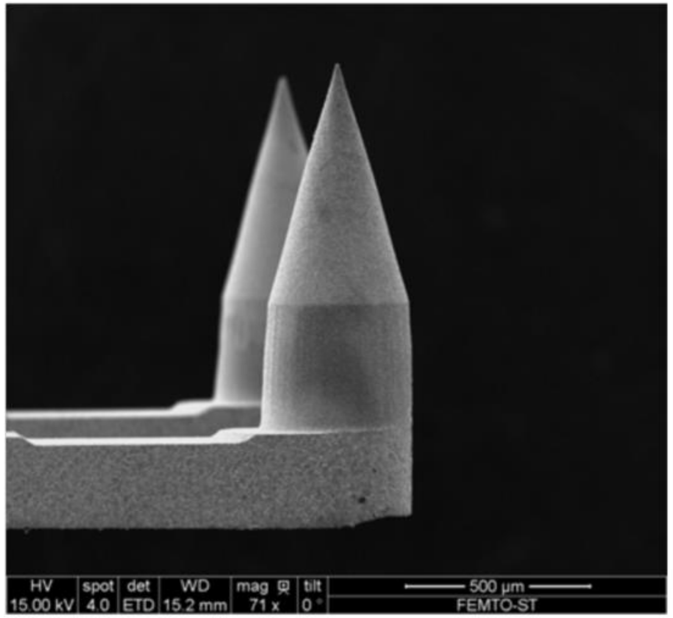
Previously, the microcantilever and the tip are glue on a piezoelectric actuator







By coupling WEDM and µMilling by EDM, one part is obtained (cantilever and tip)
3D Complex part with a controlled tip radius



Time processing : 15 hours

Processing is OK but what's the influence of process on the processing part ?

Toughness caracterisation ?

toughness is the ability of a material to absorb energy and plastically deform without fracturing

Material toughness is the amount of energy per unit volume that a material can absorb before breaking

How to perform toughness tests at micro scale ?

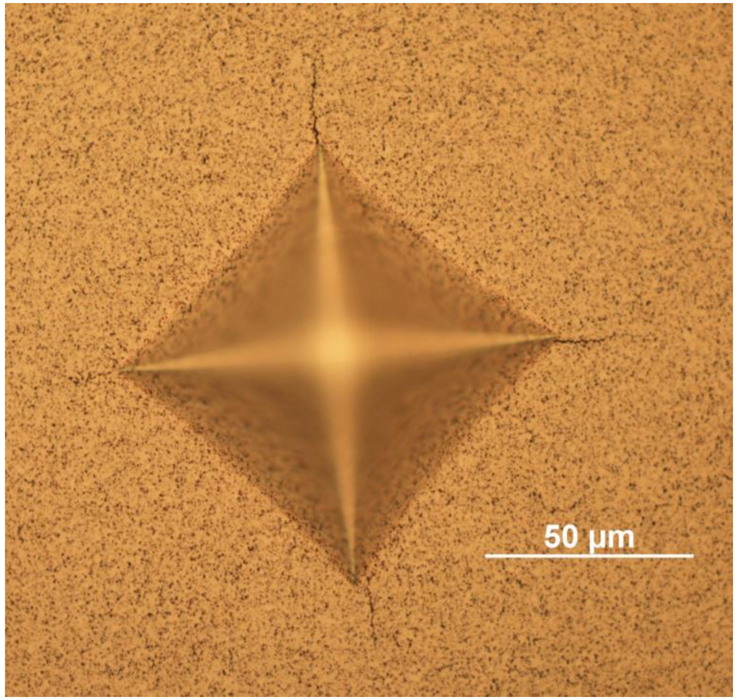
Bending test on a micro-cantilever beam by nano-indentation

Comparison with Vickers’s indentation at macro scale

Department of Applied Mechanics

Vickers's tests

Measuring the length of the cracks at each corner of the contact impression



J. Monnet, Y. Gaillard, F. Richard, S. Thibaud, 2019

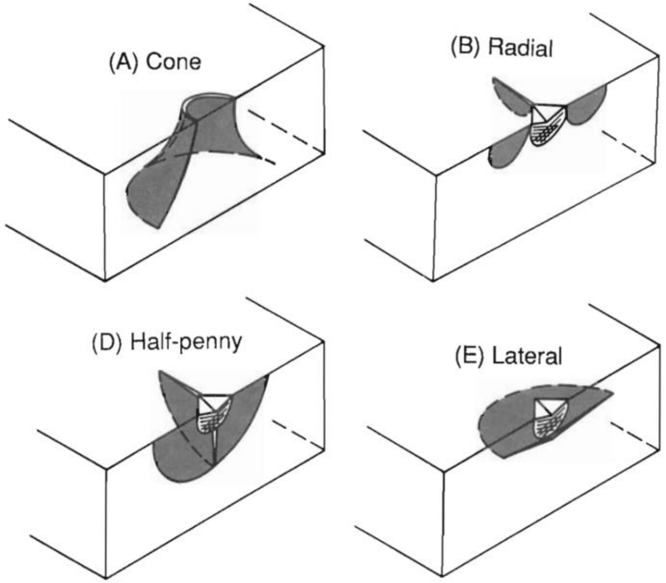


Fig. 1. Isometric sections of idealized crack morphologies observed at indentation contacts: (A) cone crack and associated nucleating ring crack, (B) radial cracks and associated contact impression and plastic deformation zone (Vickers indentor), (C) median cracks (The full circle indicates the extent just after initiation, and the truncated circle the possible extent on continued loading.), (D) half-penny cracks, and (E) lateral crack.

[Cook & Pharr 1990]

Vickers's tests

Measuring the length of the cracks at each corner of the contact impression

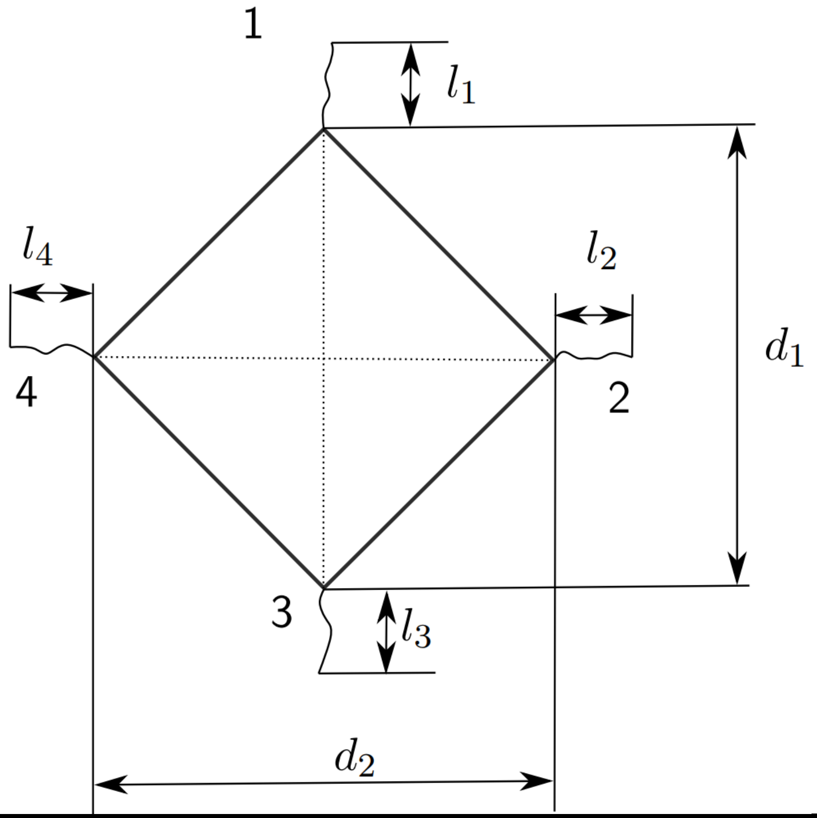
To define toughness limit, we introduce the stress intensity factor K_{IC} (MPa.$\sqrt{m}$)

Some methods : Shetty 1985, Niihara 1982, ISO 28079

$$K_{IC} = \beta \cdot \sqrt{H \cdot W}$$

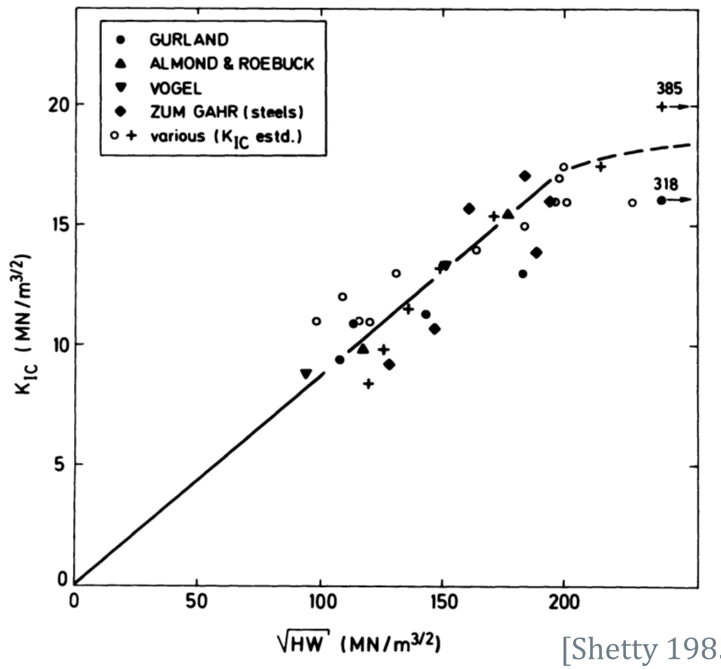
Shetty : β=0,0889
H : Vicker's hardness
l_i : cracks lengths
P : applied load

$$W = \frac{P}{\sum l_i}$$



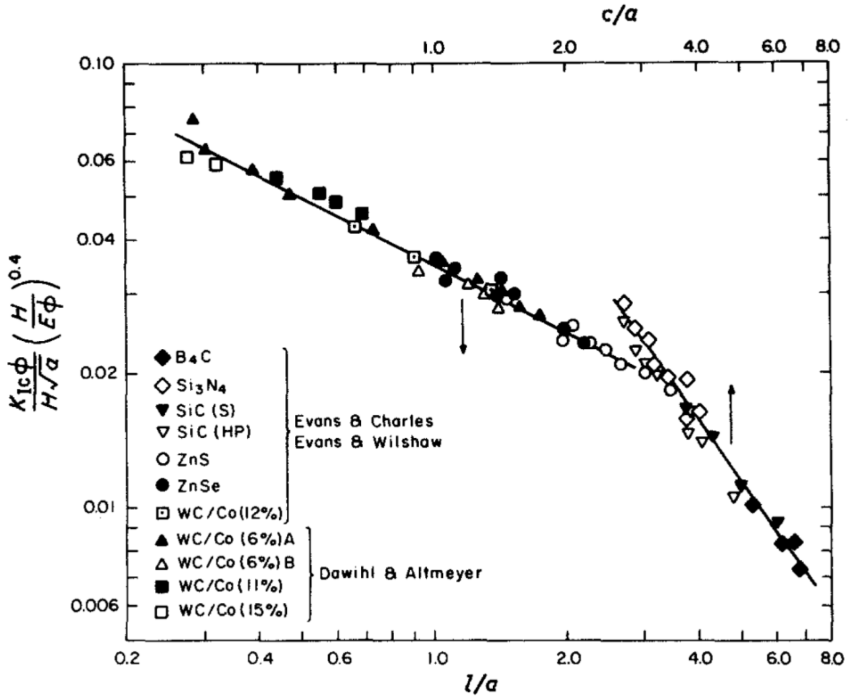
Vickers's tests

Shetty



[Shetty 1985]

Niihara

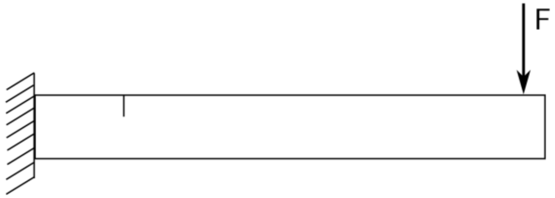


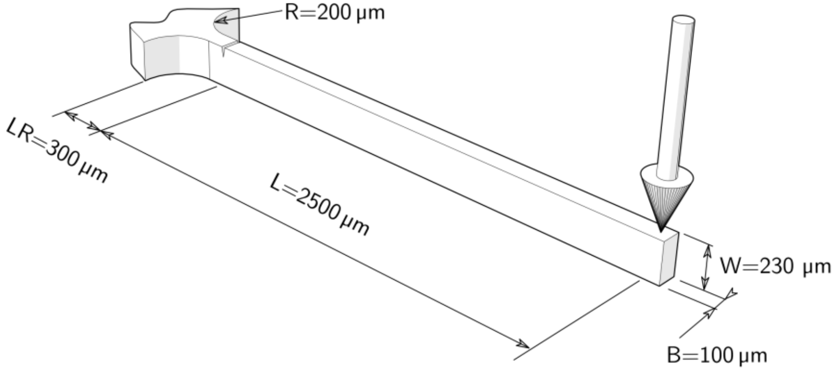
Method	Stress Intensity factor (MPa.$\sqrt{m}$)
Shetty	13.81
Niihara	15.84
ISO 28079	13.75

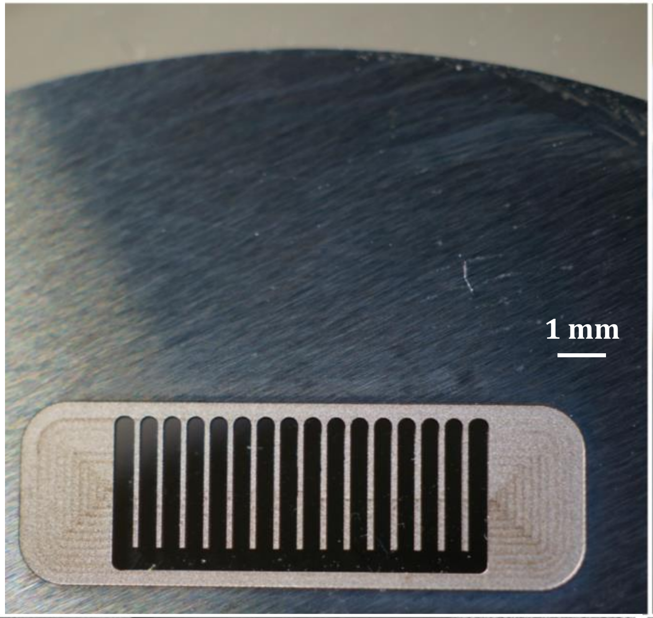
Micromachining : µEDM

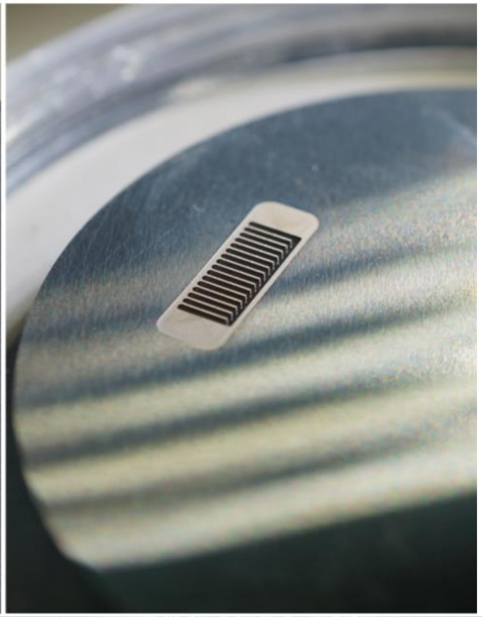
Toughness at micro-scale ?

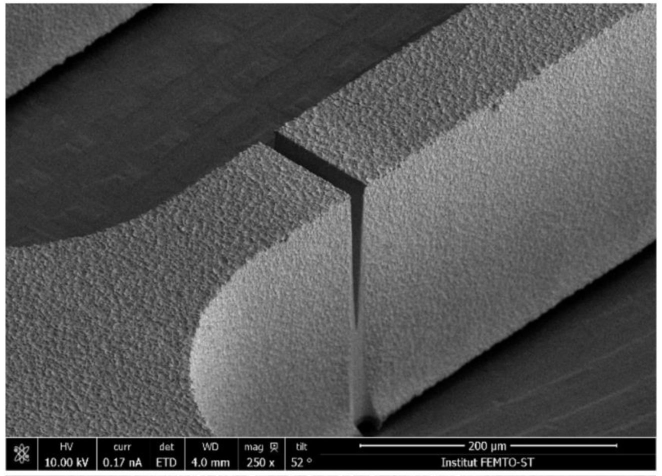
Micro-bending tests of a pre-cracks cantilever beam

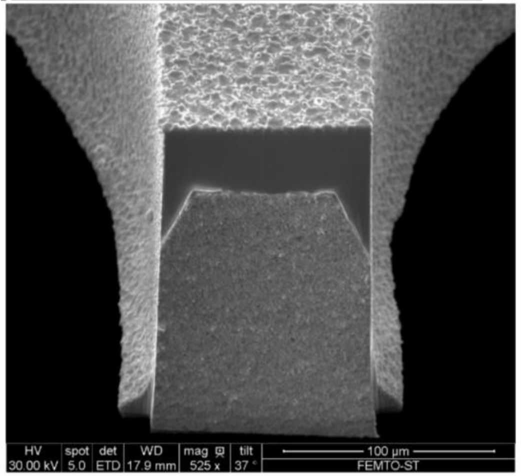








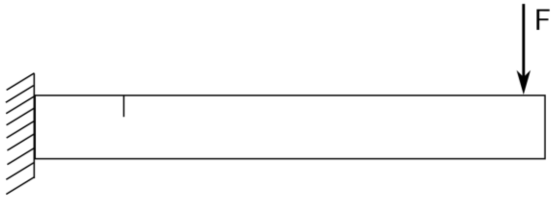


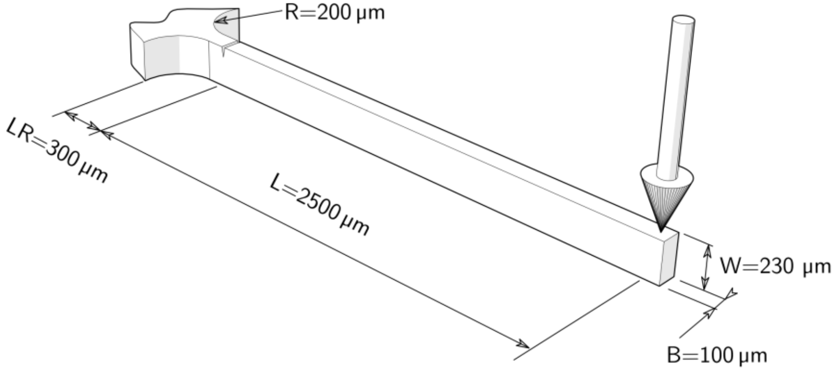


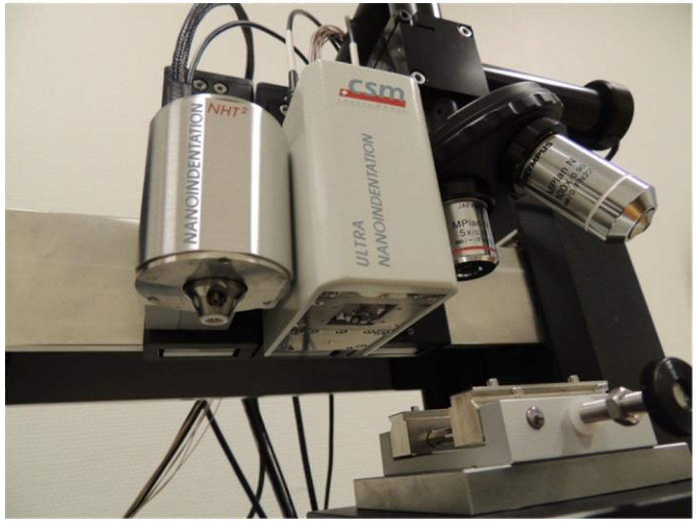
Initial cracks are obtained by focus ion beam technology

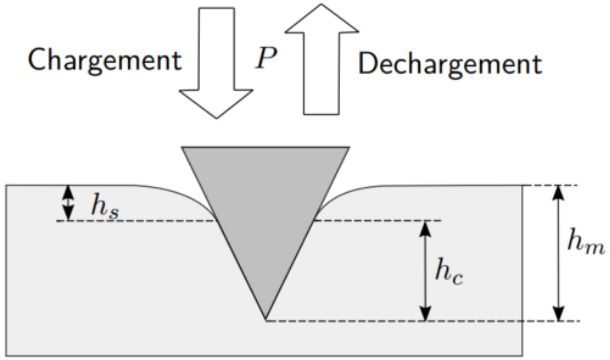
Toughness at micro-scale ?

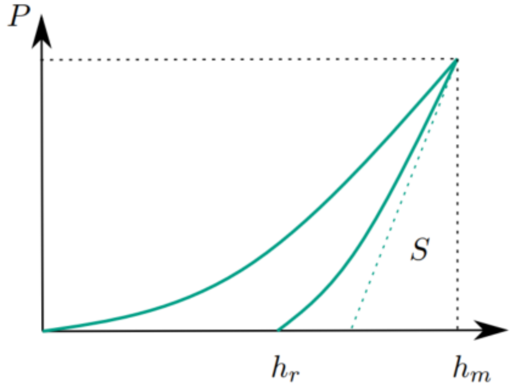
Micro-bending tests of a pre-cracks cantilever beam









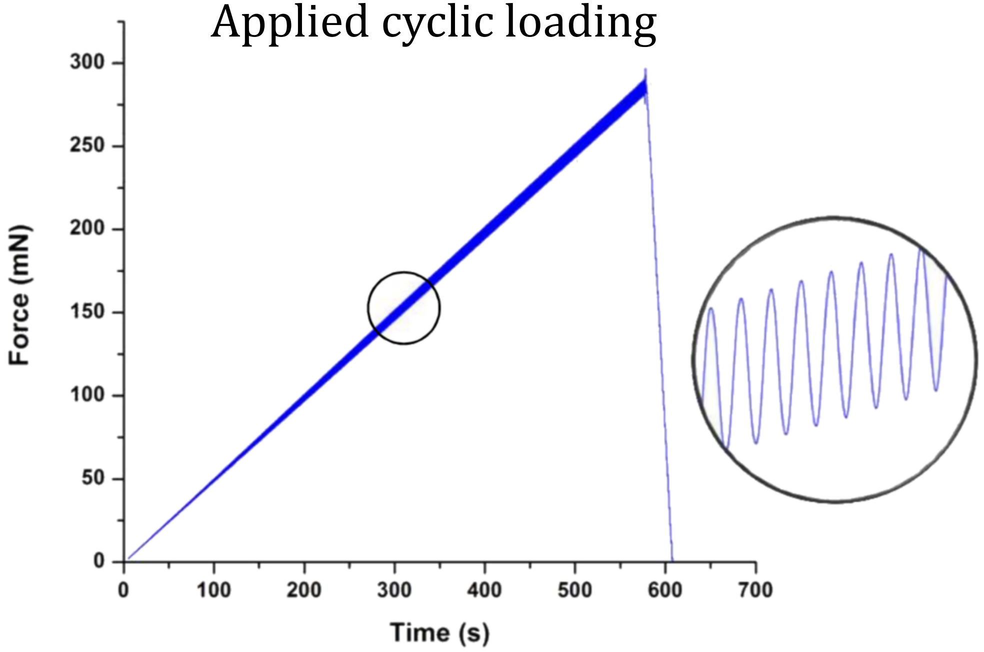


By using nano-indentation technique, repeatable instrumented micro-bending tests can be performed

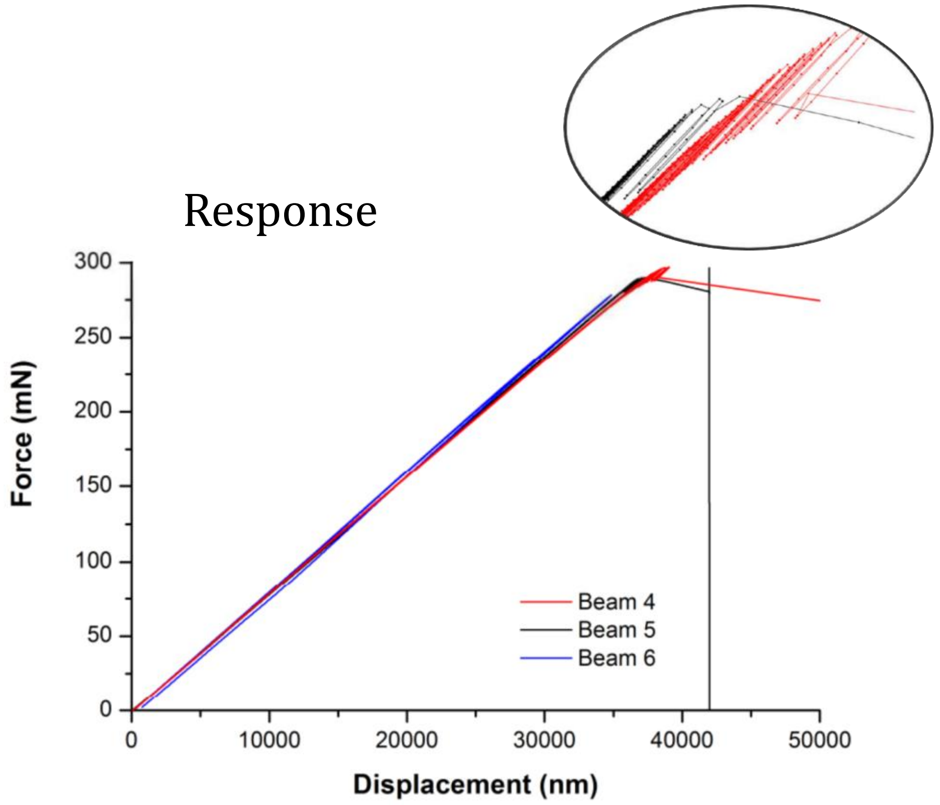
Toughness at micro-scale ?

Micro-bending tests of a pre-cracks cantilever beam

Applied cyclic loading



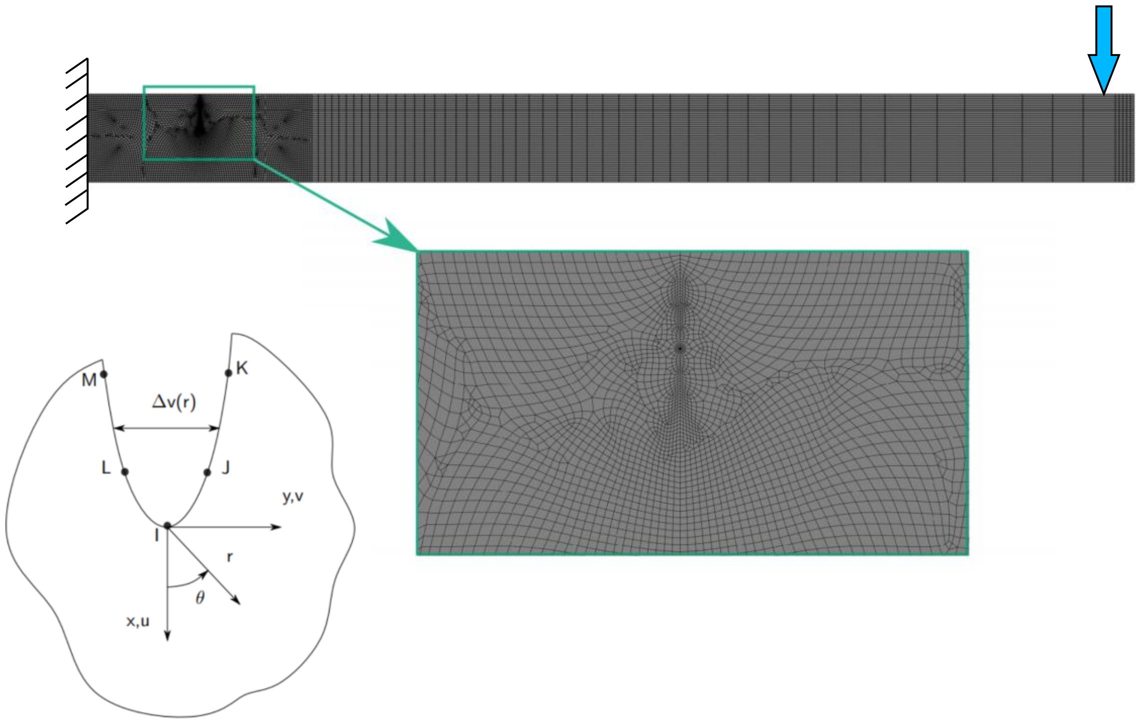
Response

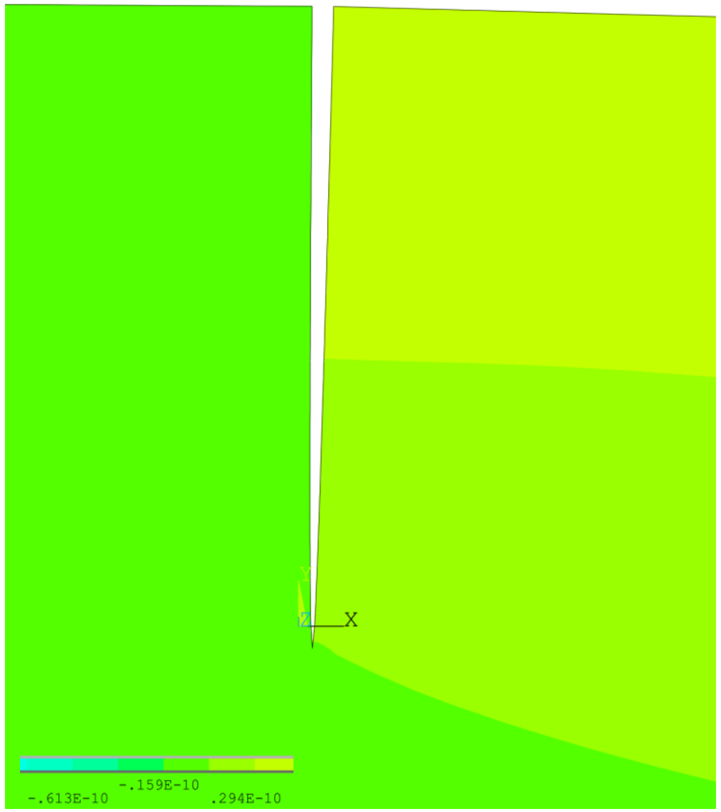


Breakage force is identified as repeatable

Identification procedure of the stress intensity factor is based on the use of an equivalent numerical model (2D Plane Stress FE Model)

From the experimental breakage force



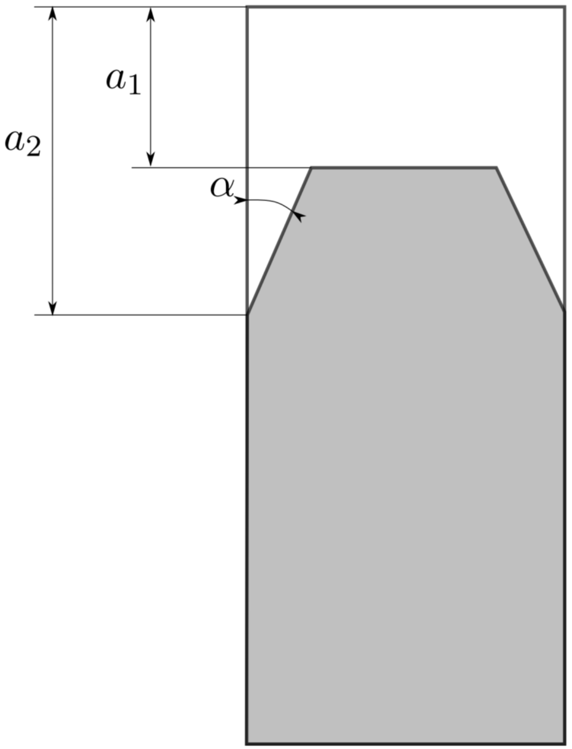


Displacement field at crack tip area (mm)

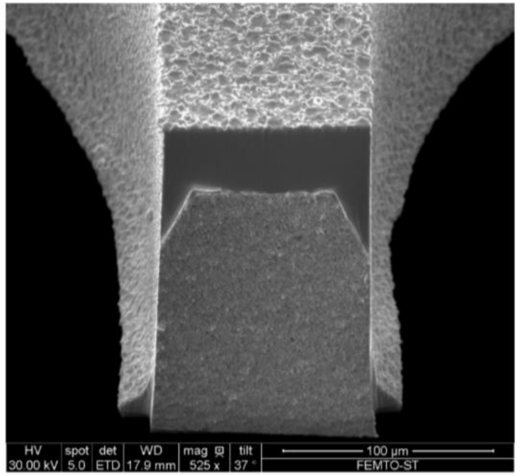
Micromachining : µEDM

Identification procedure of the stress intensity factor is based on the use of an equivalent numerical model

Influence of the initial crack profile



It is not possible to produce a perfect crack profile with FIB technique



Toughness is then calculated by considering several crack length and compared (max, min, average)

Initial Crack length a	Stress intensity Factor (MPa. $\sqrt{m}$)
a_1=52 µm	10.43
a_2=94µm	16.57
a_{mean1}=54 µm	10.675
a_{mean2}=57 µm	11.046

Micromachining : µEDM

Summary

Technique	Methods / Parameters	Stress intensity Factor (MPa. $\sqrt{m}$)
Vickers's indentation	Shetty	13.81
Vickers's indentation	Niihara	15.84
Vickers's indentation	ISO 28079	13.75
Micro-bending	a_1=52 µm	10.43
Micro-bending	a_2=94 µm	16.57

It's possible to measure stress intensity factor at micro-scale but the influence of EDM process is still being investigated

Why characterrize mechanical properties at this scale ?

Scientific approach : Scale effects ? Is toughness impacted by downscaling ?

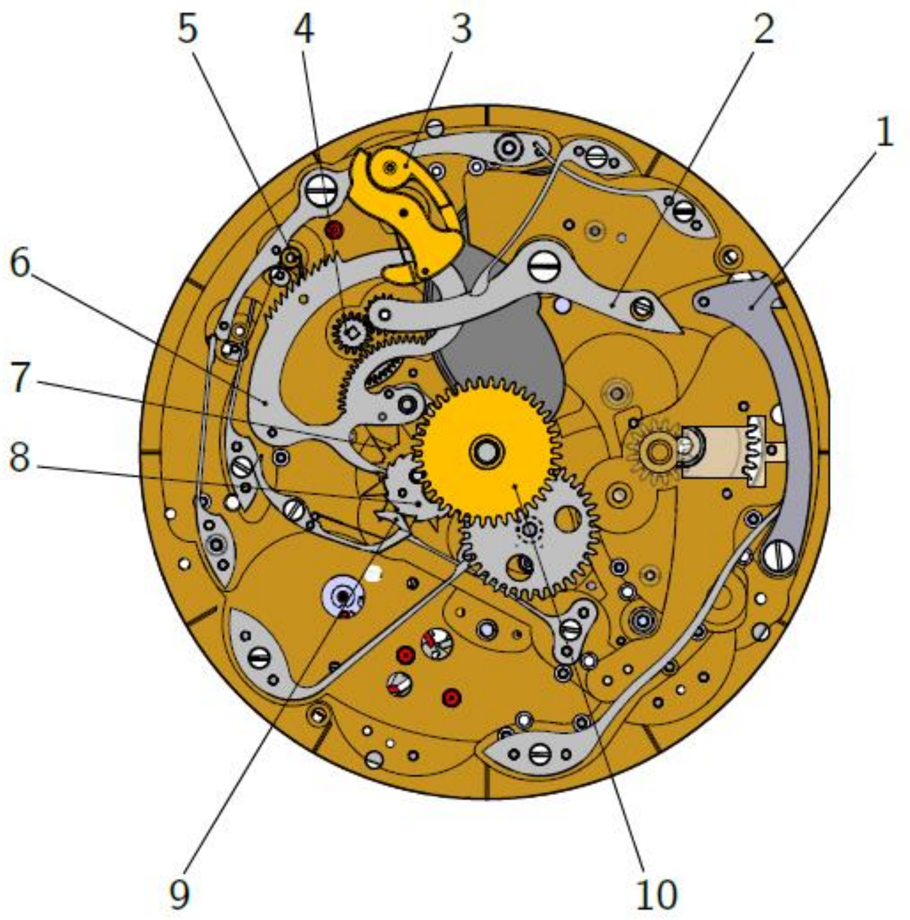
Toughness seems to increase with downscaling ....

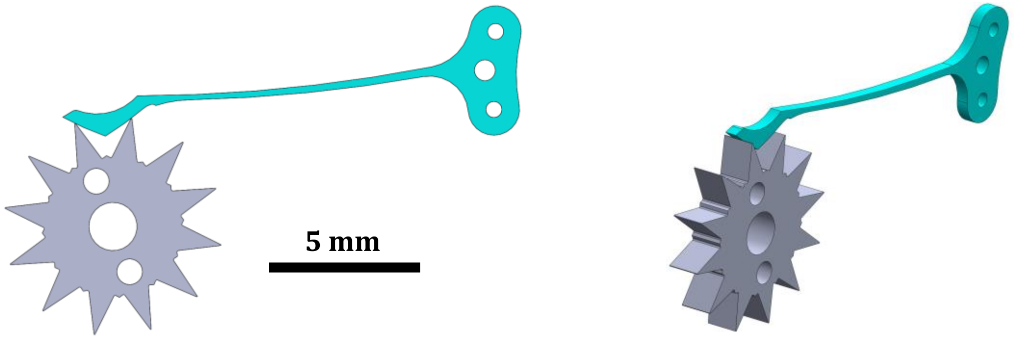
Does the EDM process introduce defects influencing toughness ? (µEDM = micro-cracks)

Tungsten carbid material is
- a very hard material
- Important wear/friction properties
- Important elastic properties (530 to 700 GPa) – elastic energy storage is potentialy more imporant than steel

Is it possible to make elastic microparts in tungsten carbid material ?

Application to watch component ?





A star jumper to index the hour reading system

Needs to :

- Decrease friction at the star/jumper contact
- Decrease wear of the two components
- Store elastic energy (power consumption)

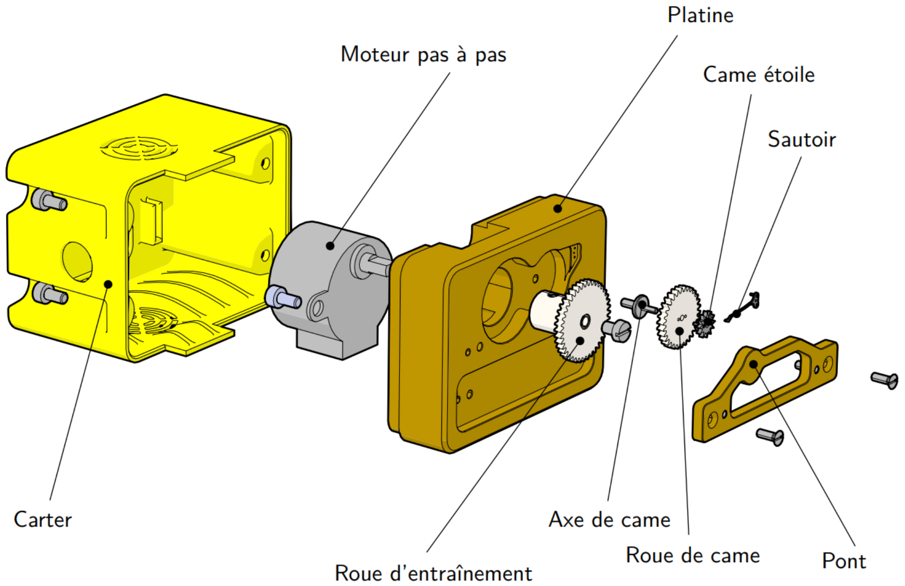
Application to watch component ?

Micromachining : µEDM

Application to watch component ?

Star jumper is a flexible part : is it possible to fabricate it in tungsten carbide material ?

Processes : WEDM and µEDM Milling to surface finishing



J. Monnet, PhD Thesis, 2019

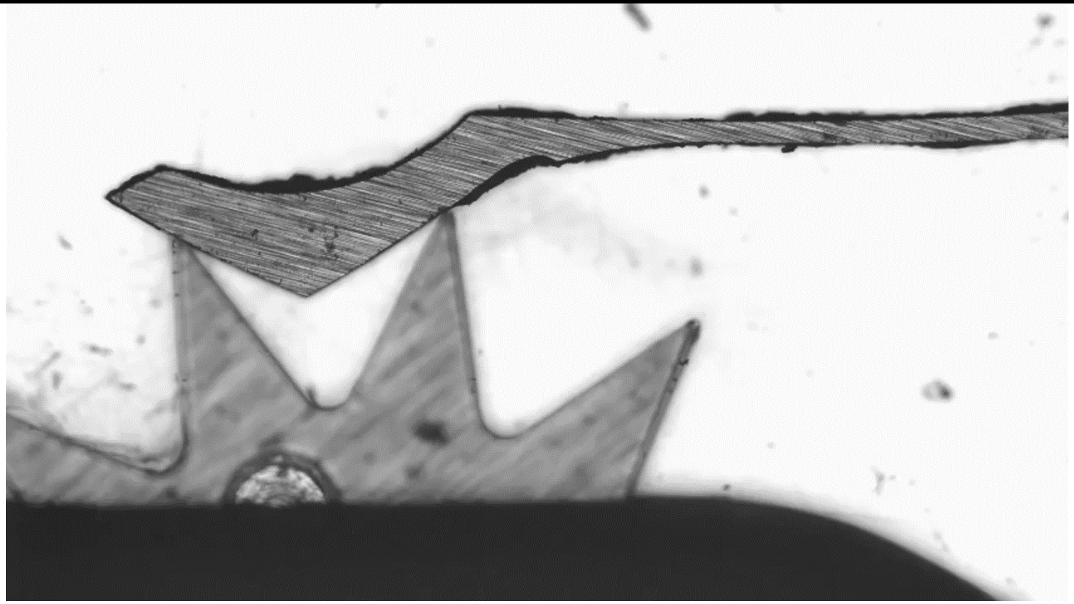
Application to watch component ?

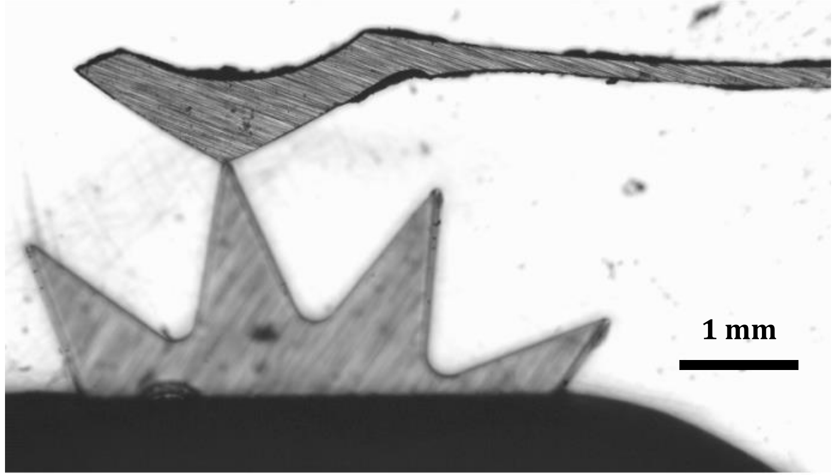
Star jumper is a flexible part : is it possible to fabricate it in tungsten carbide material ?

Application to watch component ?

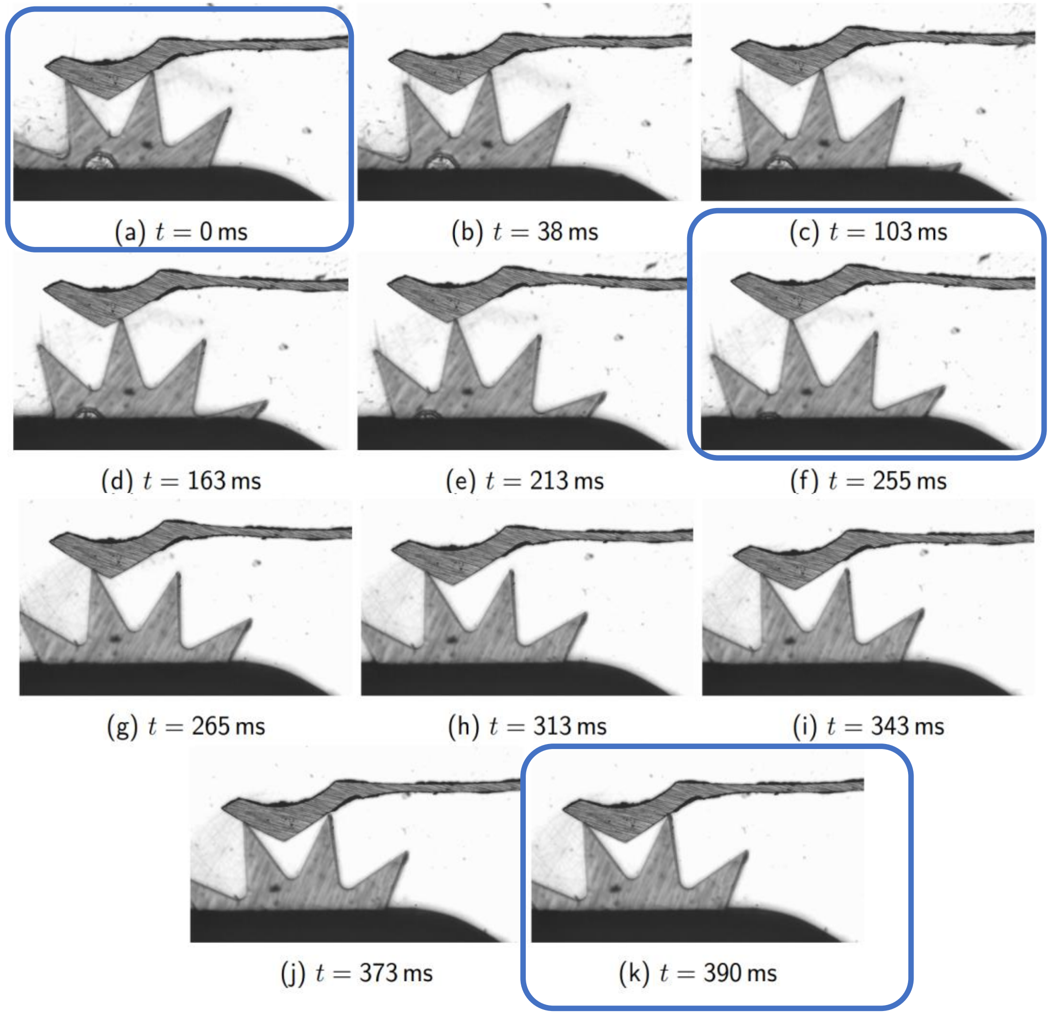
Tooth indexing capture

Data capture frequency : 1000 Hz
Images Resolution : 848 x 480 pixels
Capture time : 665 ms
Capture area : 3477 µm x 1968 µm





Kinematical analysis



Rise time = 255 ms

fall time = 135 ms

Mechanical analysis

How to determine the evolutions ot strains/stresses fields at this scale ?

By using Digital Images Correlation (Amiot et al.)

In principle in full field measurements, a pattern (speckle) is applied on the part surface

The evolution of this pattern is then measured between each images (displacement field)

By a spatial differentiation (finite difference method) it is possible to obtain strain field

Finally, by application of the stress-strain relationship (behavior law), it is possible to determine stress field

How to realize the pattern at this scale ?

In this case, we use directly the surface roughness as a pattern

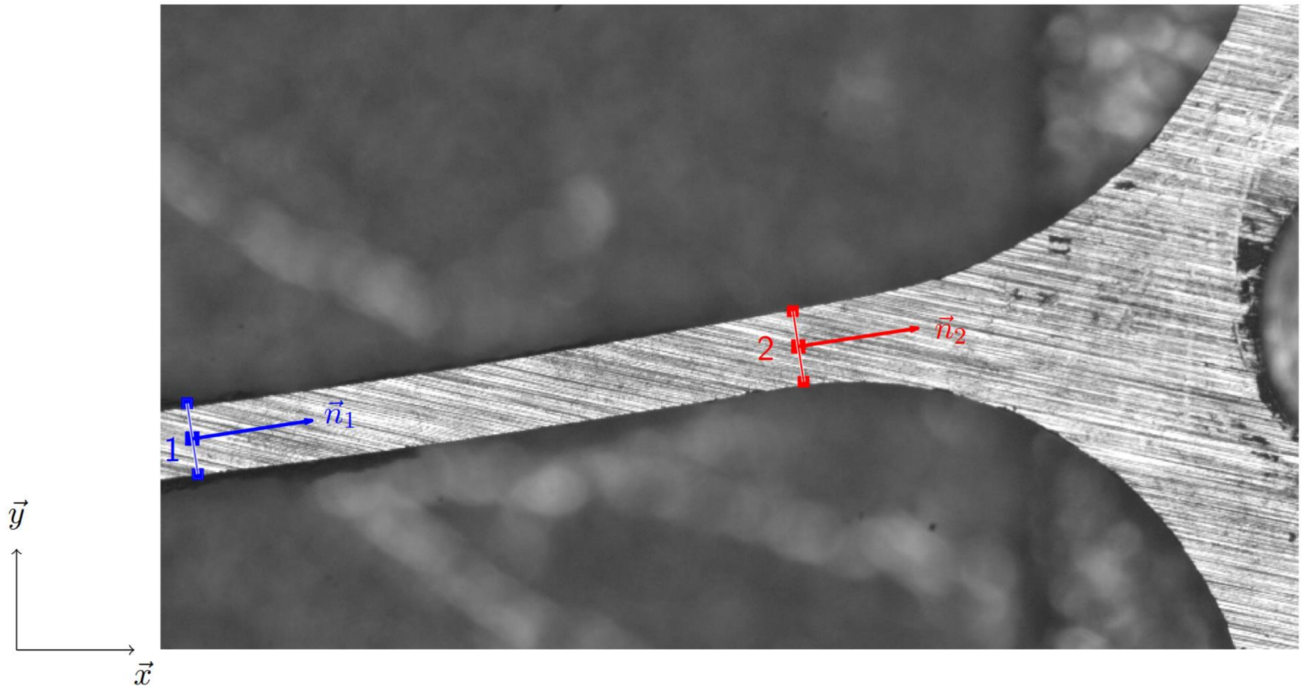
Mechanical analysis

Hypothesis #1 : we make the hypothesis that the jumper in its length can be considered as a beam

Euler-Bernoulli beam model

$$\begin{cases} N(x,t) = \int_S \sigma_{xx}\,\mathrm{d}S \\ T(x,t) = \int_S \sigma_{xy}\,\mathrm{d}S \\ M(x,t) = \int_S z\sigma_{xx}\,\mathrm{d}S \end{cases}$$

$$\begin{cases} N(x) = \rho ES\dfrac{\mathrm{d}u}{\mathrm{d}x}(x,t) \\ M(x) = -EI\dfrac{\mathrm{d}^2w}{\mathrm{d}x^2} \\ T(x) = \dfrac{\mathrm{d}}{\mathrm{d}x}\left(-EI(x)\right. \\ \dfrac{\mathrm{d}^2}{\mathrm{d}x^2}\left(-EI(x)\dfrac{\mathrm{d}^2w}{\mathrm{d}x^2}\right) = \\ \theta + \dfrac{\mathrm{d}w}{\mathrm{d}x} = 0 \end{cases}$$



If you have the elastic material properties (Young's modulus, Poisson's ratio), you can determine the evolution of the load conditions

Mechanical analysis

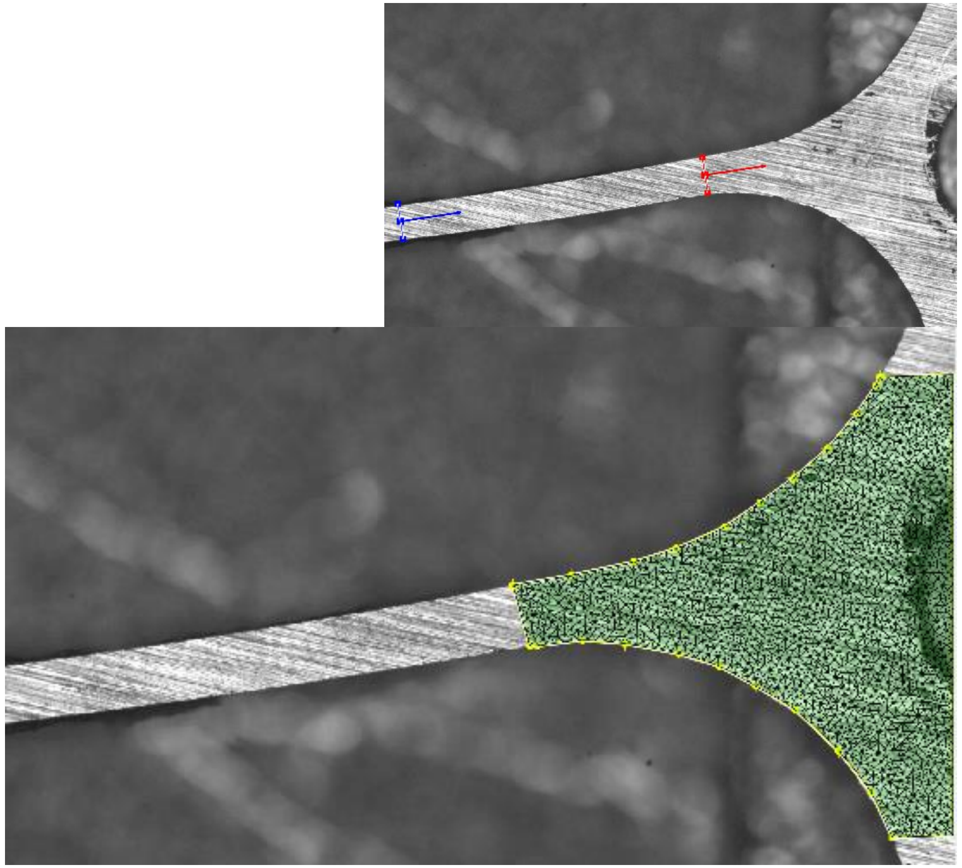
Hypothesis #2 : in the foot area, it is not possible to use a beam model

A classical full field measurements is necessary

Pattern = surface roughness

Geometrical definition = a triangular mesh with a displacement field interpolation at vertices

Mesh generation directly by edges dectection with Matlab/Octave

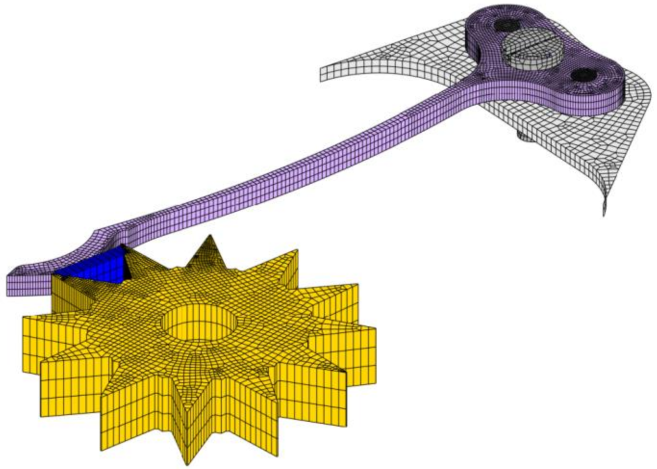


Micromachining : µEDM

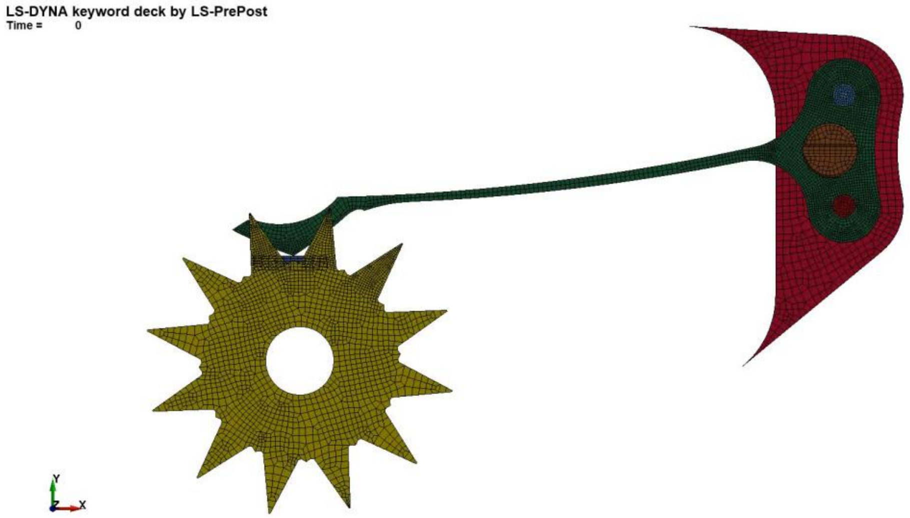
Mechanical analysis

Comparison between experiments (DIC) and a numerical model

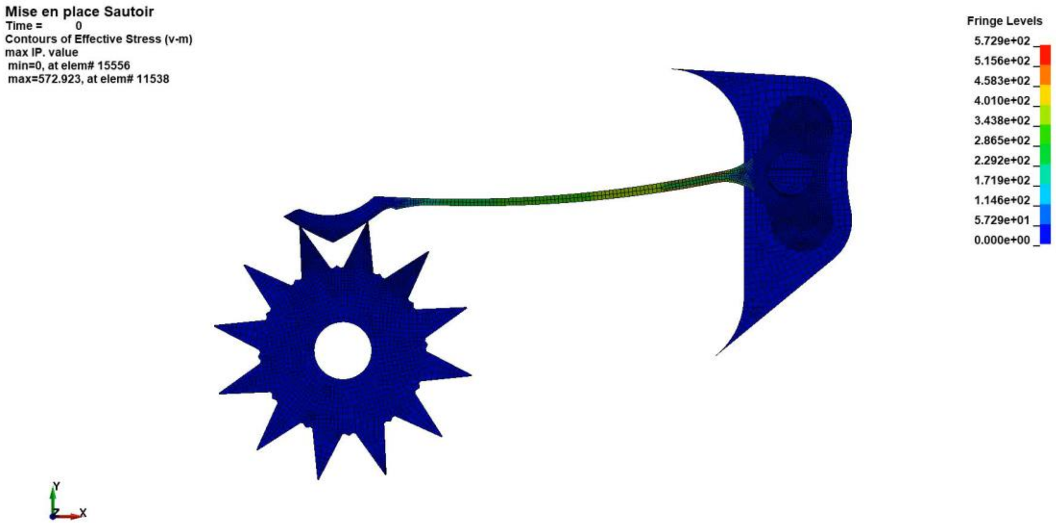
- 3D Finite Non-Linear Element model – LS-DYNA
- Implicit Dynamic time algorithm (Newmark)
- 3D Fully integrated solid elements
- Penalty Contact Algorithm
- Elastic behavior – Large Displacement / Large Rotation
- Multi-phase simulations



Phase #1 : pre-stress simulation



Phase #2 : star jump

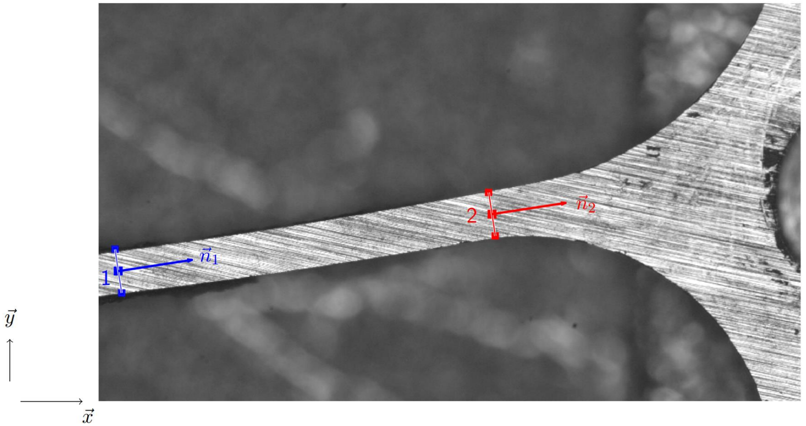


Micromachining : µEDM

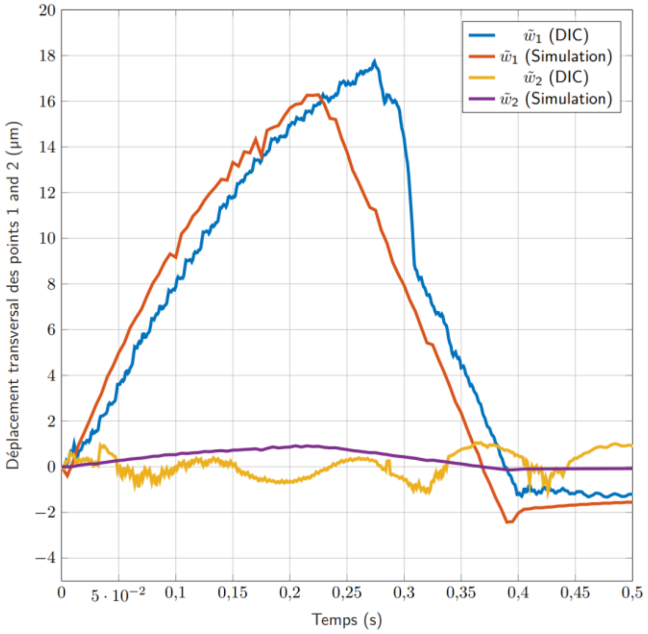
Mechanical analysis

Rotation and dilation operations between
Calculate displacement, strain and stress field in the local basis

We can use the same mesh to make Dic analysis and FE analysis



And it leads in the local beam basis



Evolutions are very close

Numerical model is validated

Delay between DIC and simulation is due to motor slowdown

Motor torque is not sufficient to obtain the correct requested speed

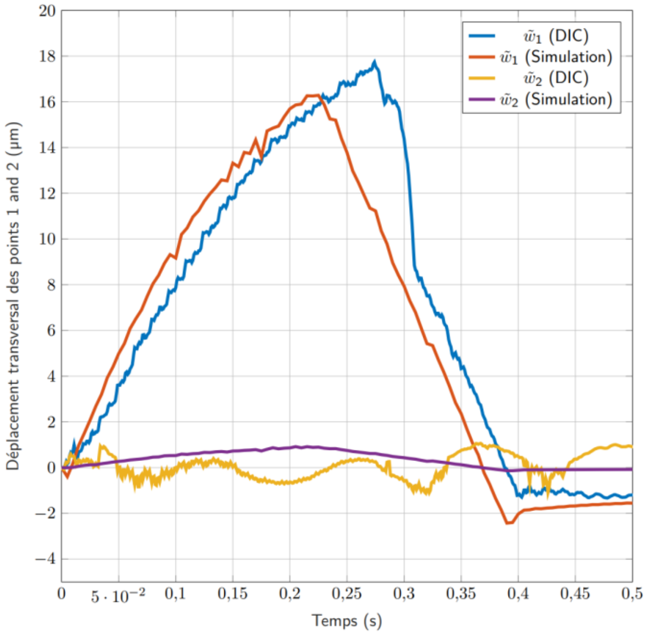
Elastic energy release is more important than motor energy

It is necessary to replace the the motor

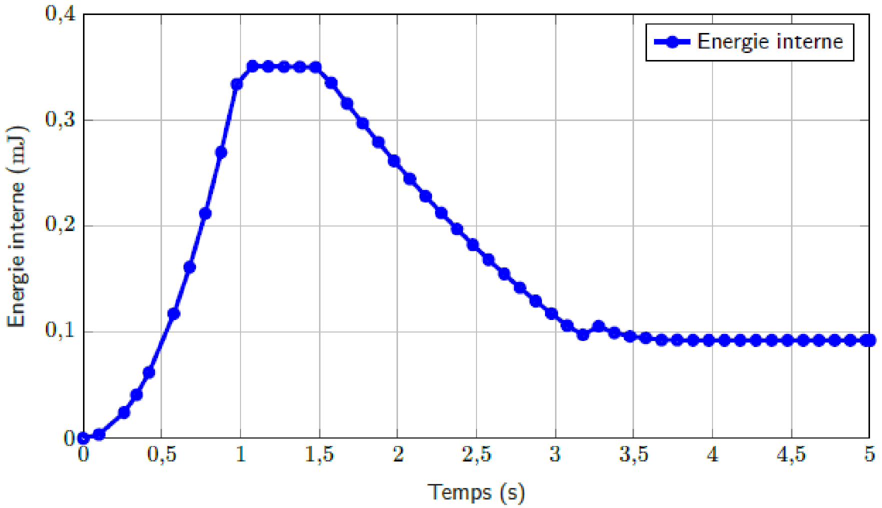
Mechanical analysis

From numerical simulation, you can observe

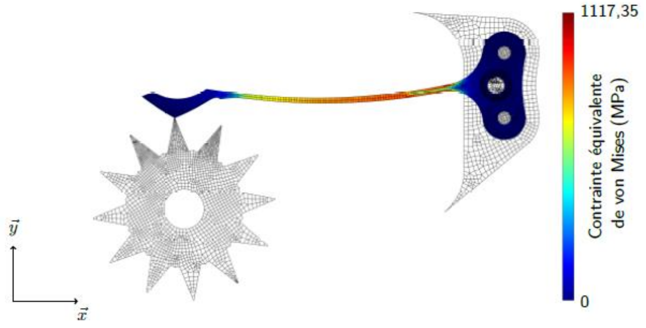
Displacements, strains, stresses



Stored energy and energy lost by friction



Check the integrity of the part



Determine the minimal crack length to ensure the integrity of the part in terms of toughness and in relation with stress intensity factor

Influence of the manufacturing process ←

Summary

µElectrical Discharge Machining is a key process in micromanufacturing of 3D complex parts in various **conductive** material

Material Removal Rate is very low at micro-scale : not for mass production of components

It is used for specifical constraints (geometries, surfaces, material, ...)

Tool's wear is a key factor to control

The local influence of the process has to take into account (micro-cracks, toughness, defects)

A strong process-material interaction is to be considered

A simple conclusion

Conclusions

Micromanufacturing processes

It's not possible to make an exhaustive nomenclature of micromanufacturing processes

It would be interesting to deepen this course towards micro-injection molding processes and coupling technologies

In microforming, blanking process is a very important process to develop

At micro-scale, scale effects are key factor to consider in order to develop micromanufacturing processes

- Microstructure Scale Effects
- Density Scale Effects
- Shape Scale Effects

A close relation between workpiece material and process has to be considered

At micro-scale, special processes are used (µEDM, microforming) and time development can be large and complex

Evaluation

Mechanical Micromanufacturing

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HIM Program – Doctoral Program