Tribology under extreme conditions devoted to manufacturing processes: methods and approaches developed at LAMIH

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of the French Society of metallurgy and materials

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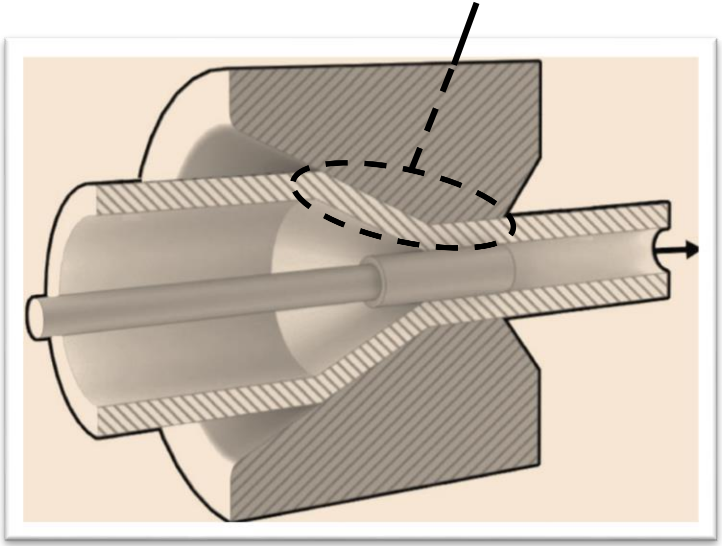
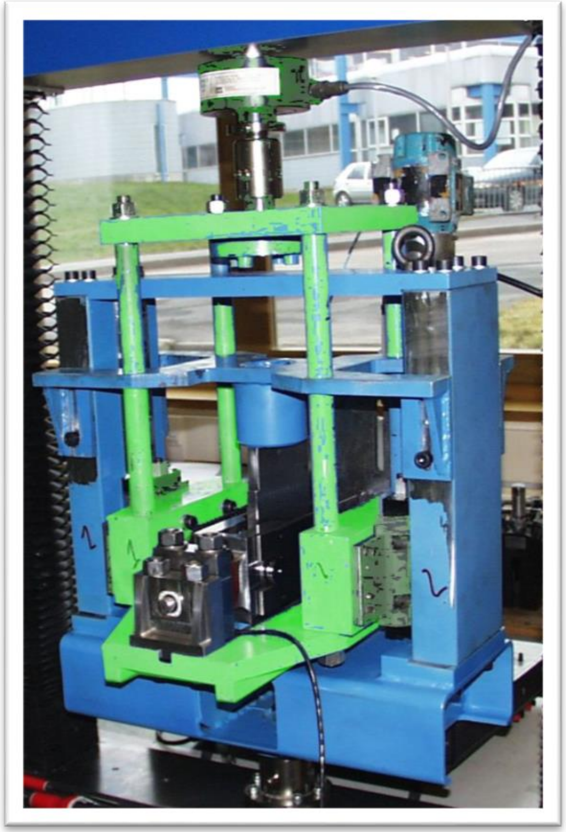
Introduction

- **1992:** A manufacturer ask the LAMIH to develop of a fast response software to improve production of steel tube drawing
  - Conclusion: results were very sensitive to friction data input
  - Need to characterise lubrication and friction (measurement of reliable friction coefficient)



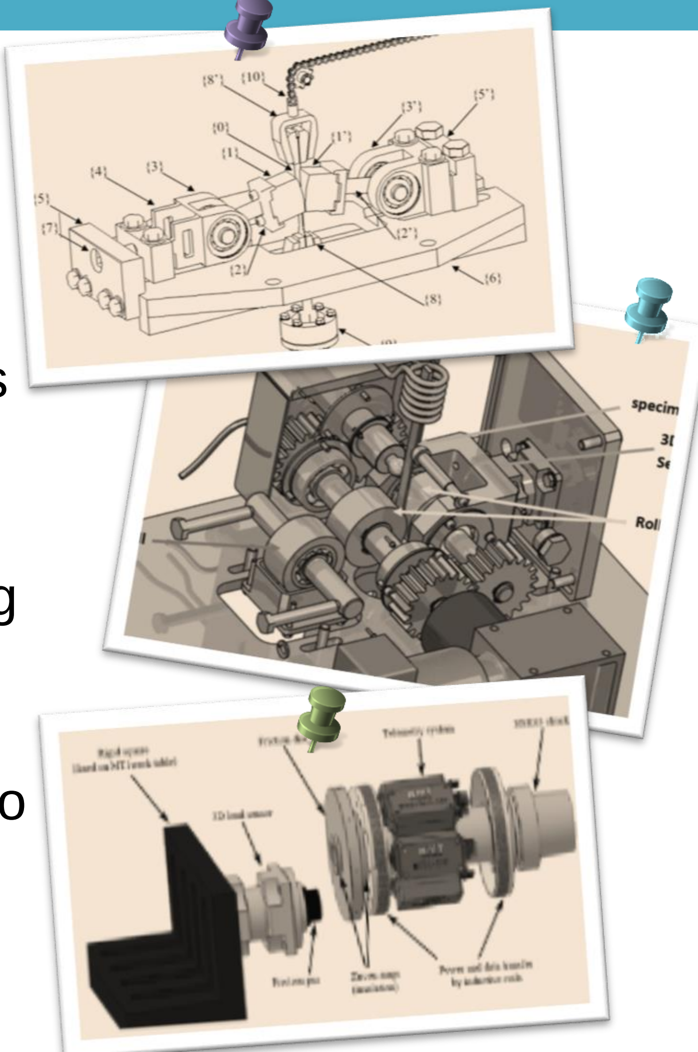
Introduction

- **1993-95: LAMIH's plan**
  - Design of a friction test able to simulate:
    - high contact pressures (> 1 GPa)
    - large plastic strains (> 1)
  - Develop the methodologies to
    - Adjust the test bench to industrial conditions of contact
    - Identify reliable coefficients of friction from test results



Introduction

- **2021: the work is still in progress**… but since 1993, we have
  - Designed 5 different friction test benches
  - Proposed an universal methodology to adjust friction tests to forming processes
  - Identified coefficients of friction according to various friction models
  - Applied the methodology to cold and hot metal forming processes, to sliding and to **rolling contact** (forging, stamping, rolling, machining)

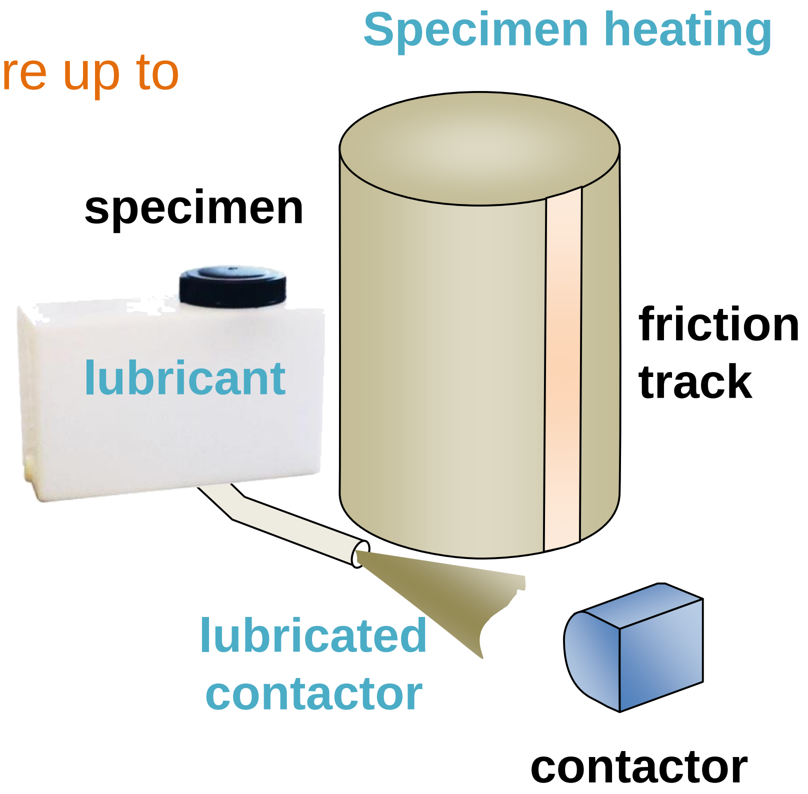


Introduction

- Summary
  - Main design of LAMIH's benches
  - How to identification reliable Coulomb's coefficients and constant friction factors
  - Methodology
  - Main issues of the tribology of metal forming
  - Some studies:
    - Lubricant efficiency
    - Tools wear
    - Modelling of mixed lubrication
    - Surface cleanliness and lubricant efficiency

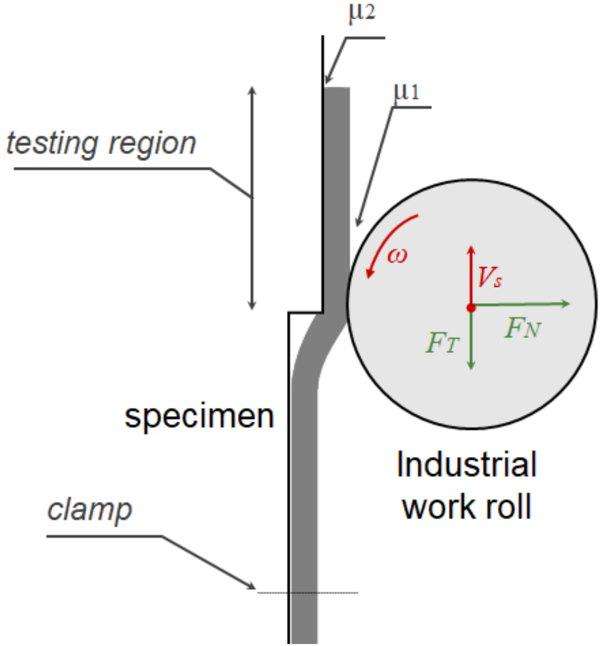
The test benches (sliding contact)

- Specimen heating from room temperature up to 1200°C. Contactor heating up to 300°C
- Contactor penetration within the specimen: contact pressure and plastic strain adjustment
- Lubricant application:
  - Solid coating or spraying of liquid lubricant
  - Applied on contactor or specimen
- Sliding speed (from 0.01 to 0.5 m.s^{-1}).



The test benches (rolling contact)

- Specimen heating from room temperature up to 1200°C. Roll heating up to 100°C
- Roll penetration within the specimen: contact pressure and plastic strain adjustment
- Lubricant application:
  - Solid coating or spraying of liquid lubricant
- Sliding displacement Vs
- **Rolling speed ω**



control of the neutral point localisation

(contact zone where the inversion of sliding velocity takes place and where the friction stress is null)

The test benches

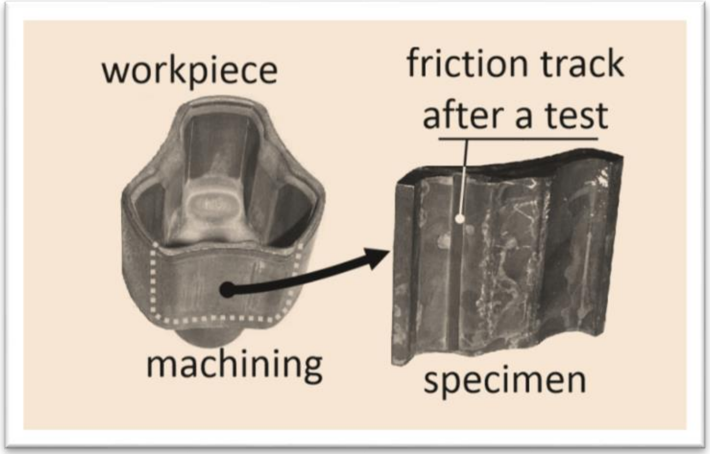
Specimens

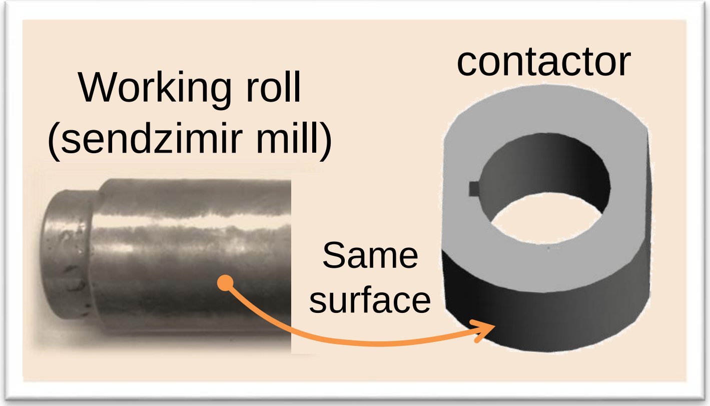
➡ Machine from industrial workpieces

\+ Contactors

➡ Machined from industrial tools

= Respect the materials, roughness, chemistry of the process



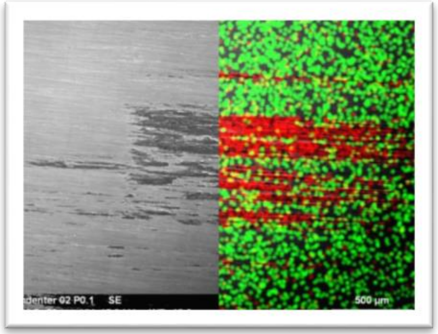


The test benches

Main test results:

- **Mechanical data**
  - Tangential et normal forces
- **Physical data**
  - Contactor and specimen roughness
  - *Specimen final temperature*
- **Metallurgical data**
  - SEM-EDS analyses

Design of the normal force sensor
Contactor are placed in the groove



Galling of aluminium alloy
SEM-EDS of contactor surface

Roughness and EDS analyses are performed before and after the test

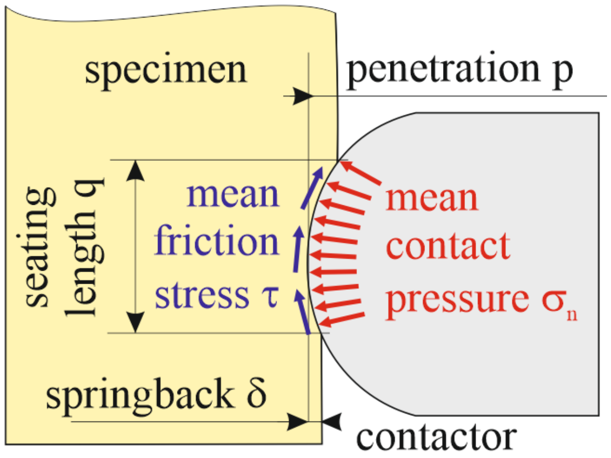
The test benches

- From forces acquisition:
  - Mean contact pressure

$$\sigma_n = \frac{(p-\delta)F_T + qF_N}{L\left[q^2 + (p-\delta)^2\right]}$$

  - Mean friction stress *(sliding contact)*

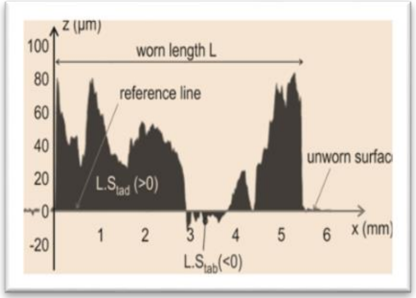
$$\tau = \frac{qF_T - (p-\delta)F_N}{L\left(q^2 + (p-\delta)^2\right)}$$



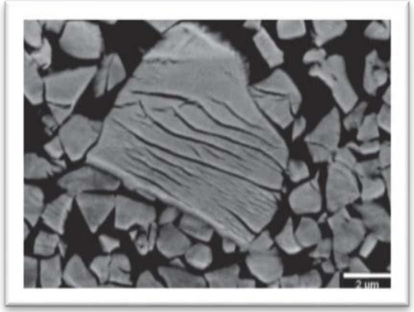
UST, WHUST: schematic view of contact zone

The test benches

- Aim of surface analyses
  - roughness: quantification of adhesive and abrasive wear, information on micro lubrication regime



  - Micrograph: measurement of macroscopic defects (scratch, crack)
  - SEM/SEM-EDS: observation and quantification of
    - grain deformation, grain removal
    - material transfer
    - residual lubricant



Identification of friction coefficients

- Main friction models in bulk metal forming:
  - The Coulomb's friction model: $\tau = \mu \sigma_n$
  - The Constant friction model: $\tau = m \frac{\sigma_0}{\sqrt{3}}$
  - The generalised friction model: $\tau = f \alpha \frac{\sigma_0}{\sqrt{3}}$

τ = friction stress

σ_n = contact pressure

σ_0 = yield stress

μ: coef. of friction ($0 \leq \mu \leq +\infty$)
m: friction factor ($0 \leq m \leq 1$)

f: friction factor at asperity scale($0 \leq f \leq 1$)
α: ratio real/apparent surface ($0 \leq \alpha \leq 1$)

Identification of friction coefficients

- Coulomb's coefficient of friction μ:

- $$\mu = \frac{\tau}{\sigma_n} = \frac{q\frac{F_T}{F_N} - (p-\delta)}{(p-\delta)\frac{F_T}{F_N} + q}$$

direct identification from test results (forces and test input parameters)

Identification of friction coefficients

- friction factor m:

- $$m = \frac{\tau\sqrt{3}}{\sigma_0} = \frac{\sqrt{3}\left[qF_T - (p-\delta)F_N\right]}{\sigma_0 L\left[q^2 + (p-\delta)^2\right]}$$

problem: the yield stress is not a friction test results

σ_0 has to be identified in the vicinity of the contact zone

Hardness measurements: easy, fast, reliable, **but** only for cold forming

FEM computations: for cold or hot forming. **Problem**: reliability of the behaviour law at high temperature?

Identification of friction coefficients

- **what if the behaviour law is not accurate?**
  - **Example** of sol-gel coating developed **for hot forging tool**
    - *contactor: stainless steel with α-alumina sol-gel coating, 250°C*
    - *specimens: 25MnCr5, 1100°C*
    - *Contact pressure: 360 MPa, sliding velocity: 60 mm.s^{-1}, no lubricant*
  - WHUST results
    - Mean friction stress: **101 MPa**
    - Yield stress computed with
      - a Hansel-Spittel behaviour law: **152 MPa** ⇒ ~~**m = 1.15**~~ **> 1: IMPOSSIBLE**
      - an incremental formulation: **245 Mpa** ⇒ **m = 0.71**

        (Puchi-Cabrera et al.)

Identification of friction coefficients

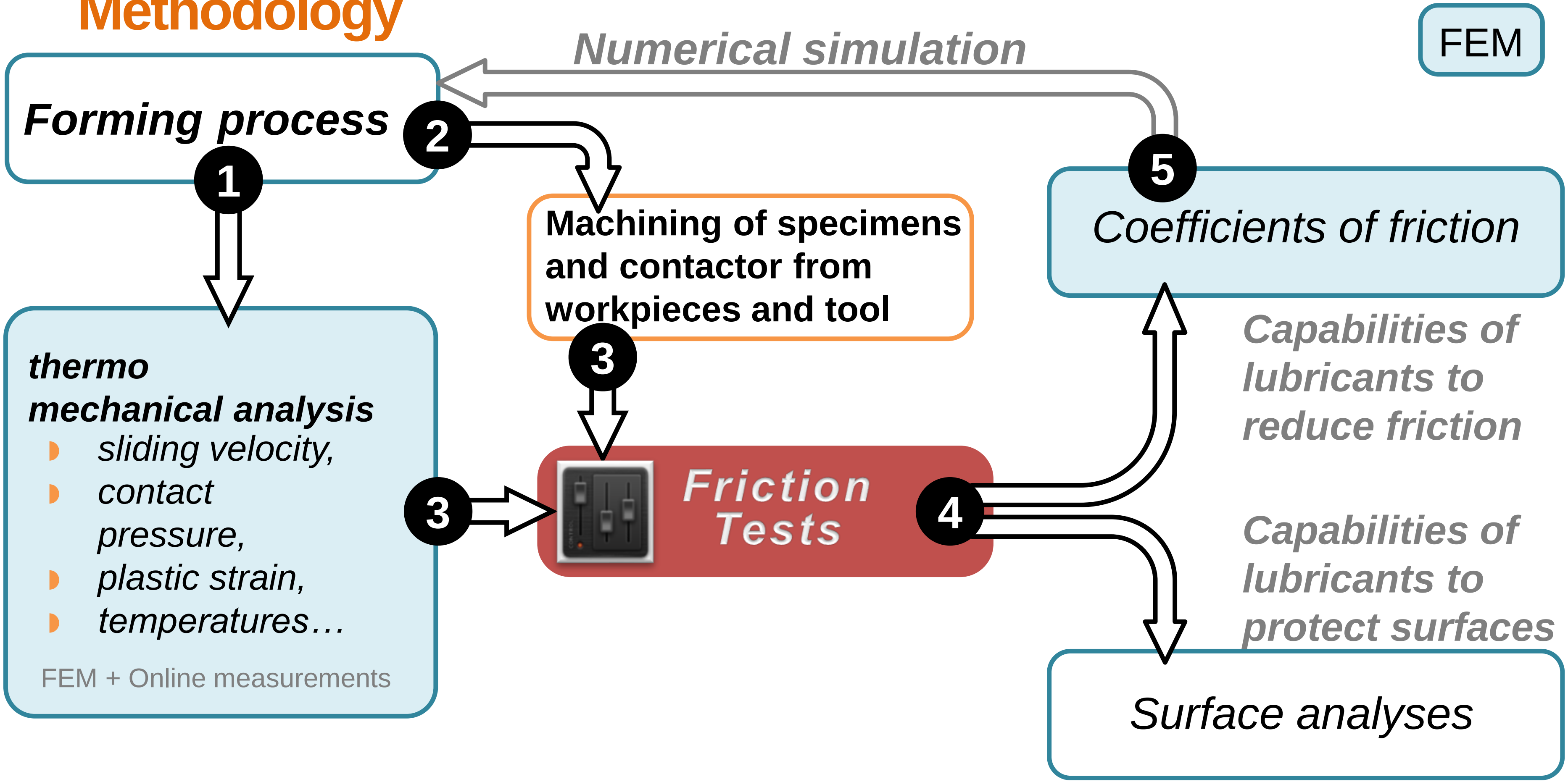
- Generalised friction coefficient f:

$$f = \frac{\tau\sqrt{3}}{\alpha\sigma_0} = \frac{\sqrt{3}\left[qF_T - (p-\delta)F_N\right]}{\alpha\sigma_0 L\left[q^2 + (p-\delta)^2\right]}$$

FEM Inverse identification
Problem: the generalised friction law has to be implemented in the FE software

problem: σ_0 and α are unknown

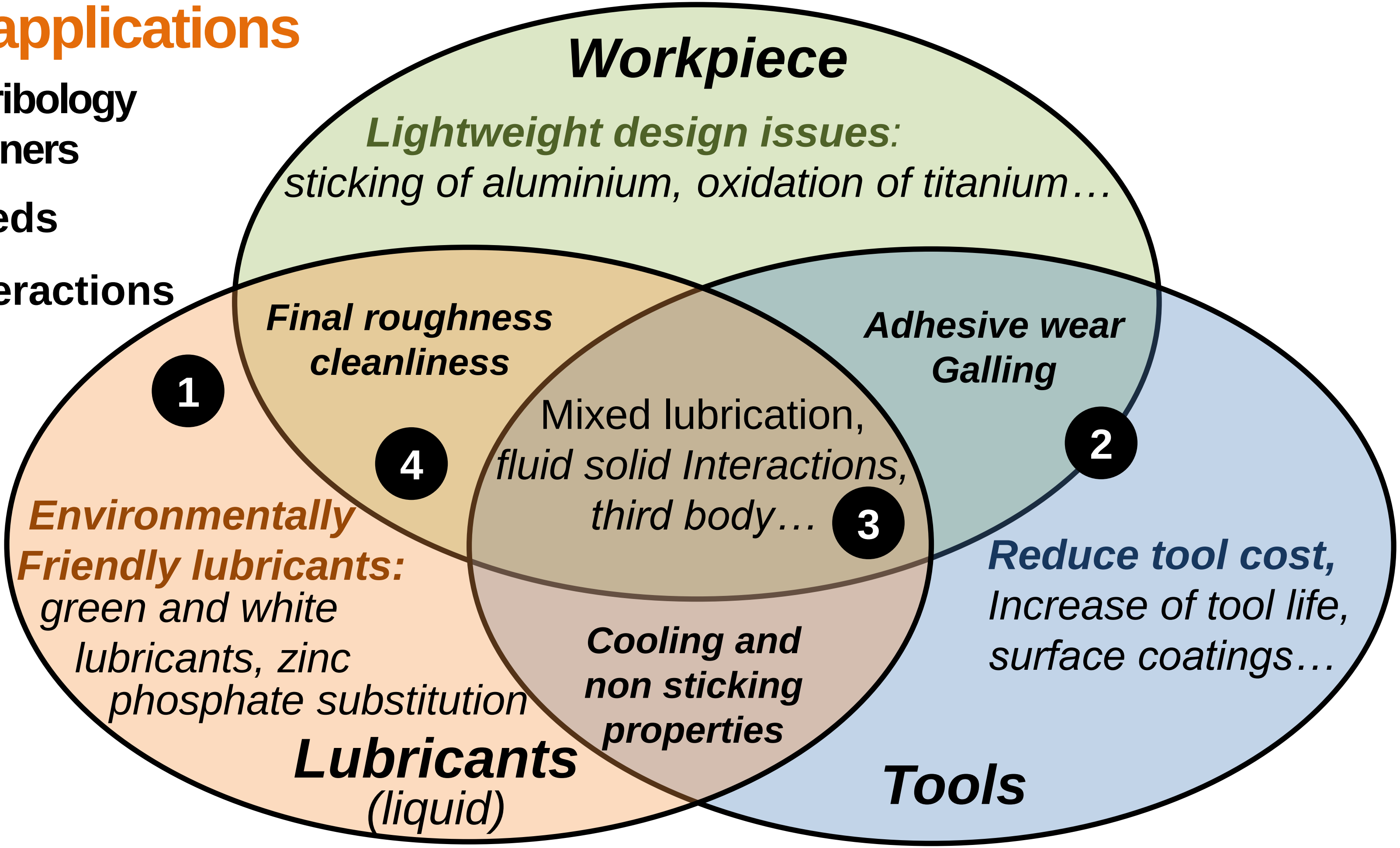
Methodology



Some applications

Issues in Tribology

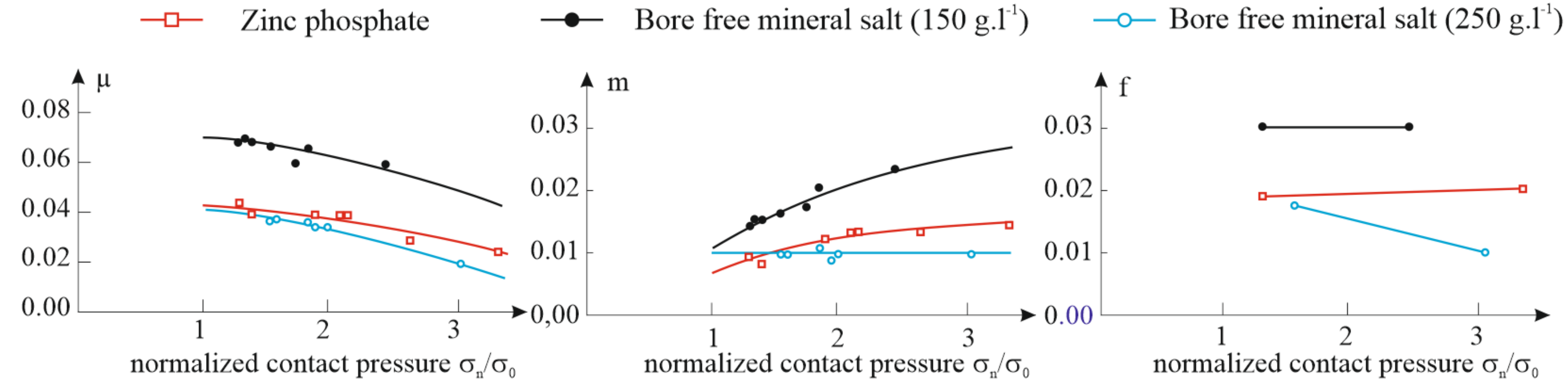
- The partners
- The needs
- The interactions



Some applications

1 Testing of lubricants in cold forging

Testing of solid lubricant. Which coefficients of friction should be identified?



Coulomb's coefficient of friction depends on the contact pressure:

- ➡ not efficient for metal forming
- ➡ Must be identified at a contact pressure equal to the process one

Friction factor becomes constant for salt concentration of 250 g.l^{-1}

- ➡ change of the lubrication regime from boundary to thick solid film

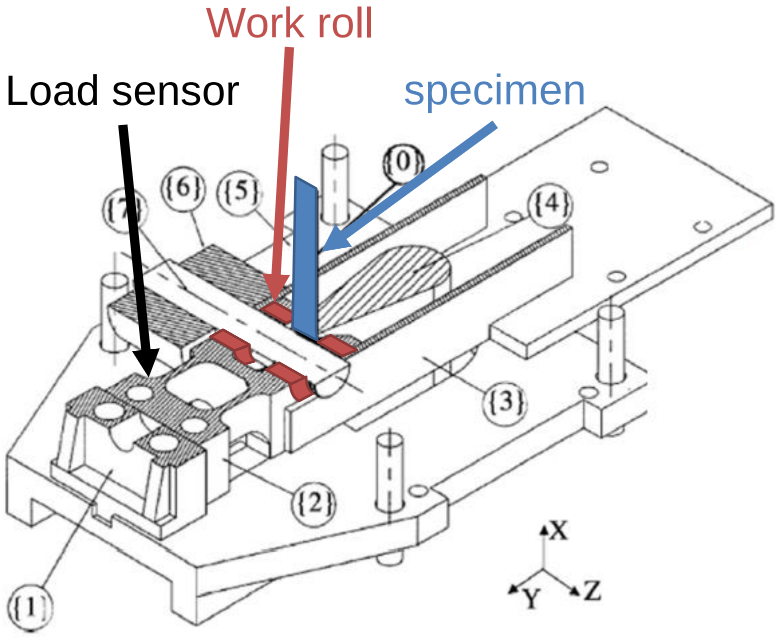
Bay's coefficient is constant for zinc phosphate and 150 g.l^{-1} salt lubricant:

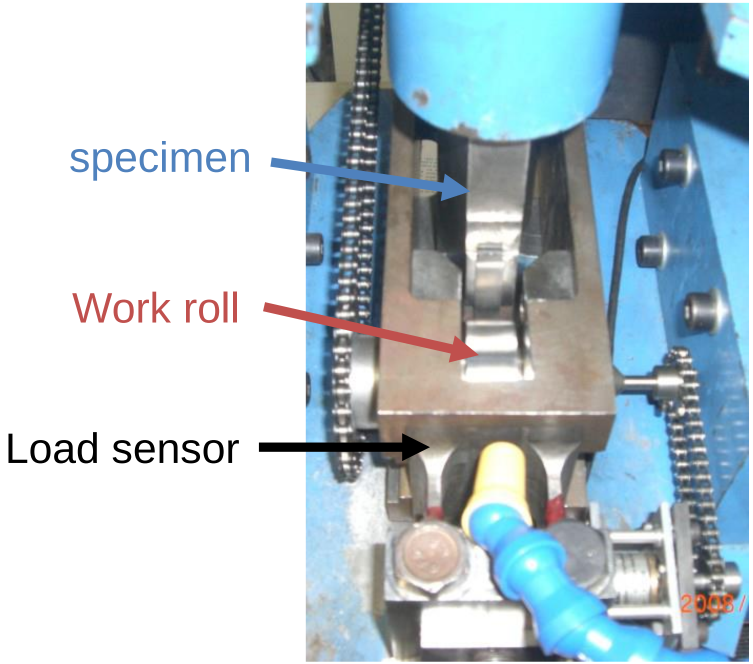
- ➡ Efficient friction model for boundary lubrication regime

Some applications

1 Testing of lubricants in cold rolling

Testing of liquid lubricant. Effect of lubricant additives on surface protection.

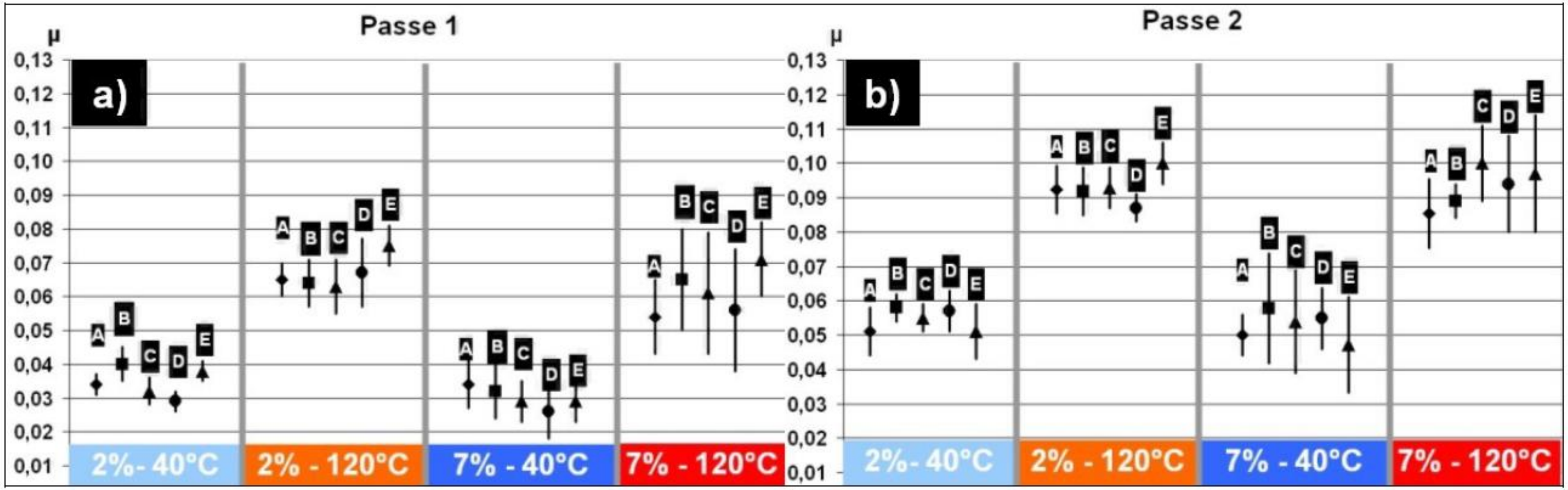




Some applications 1 Testing of lubricants in cold rolling

Testing of liquid lubricant. Effect of lubricant additives on surface protection.

A, B, C, D, E: 5 commercial oils



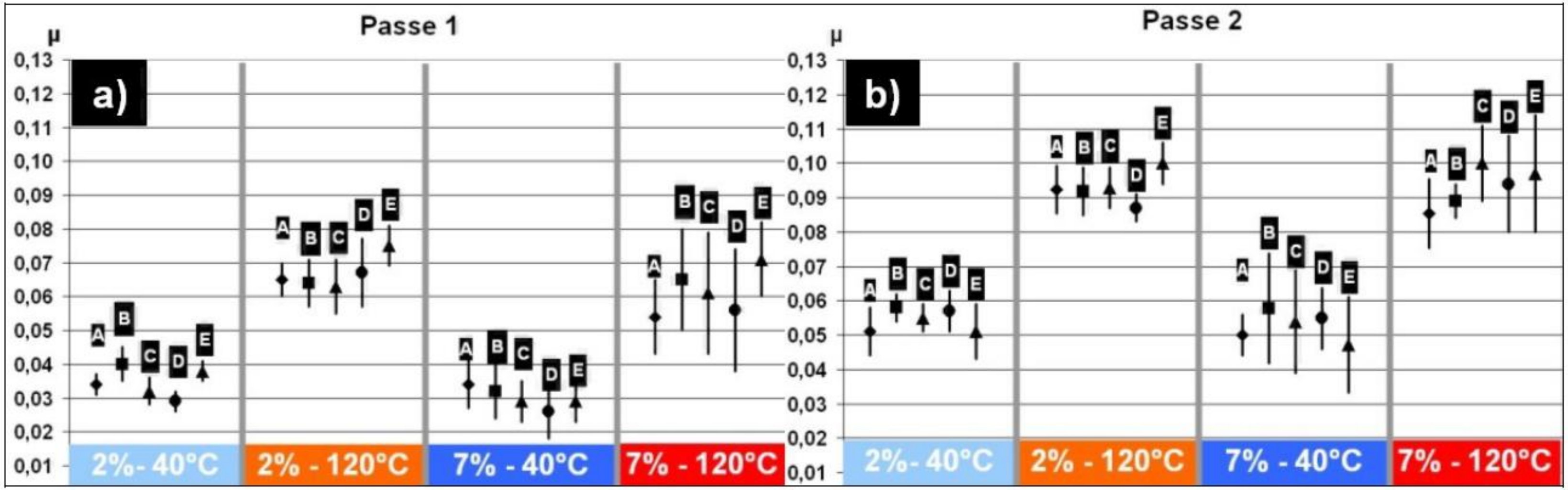
Effect of strip reduction (passe1: first reduction 28%, passe2: second reduction 28%), forward slip (2% or 7%) and roll temperature on the coefficient of friction

Some applications

1 Testing of lubricants in cold rolling

Testing of liquid lubricant. Effect of lubricant additives on surface protection.

A, B, C, D, E: 5 commercial oils

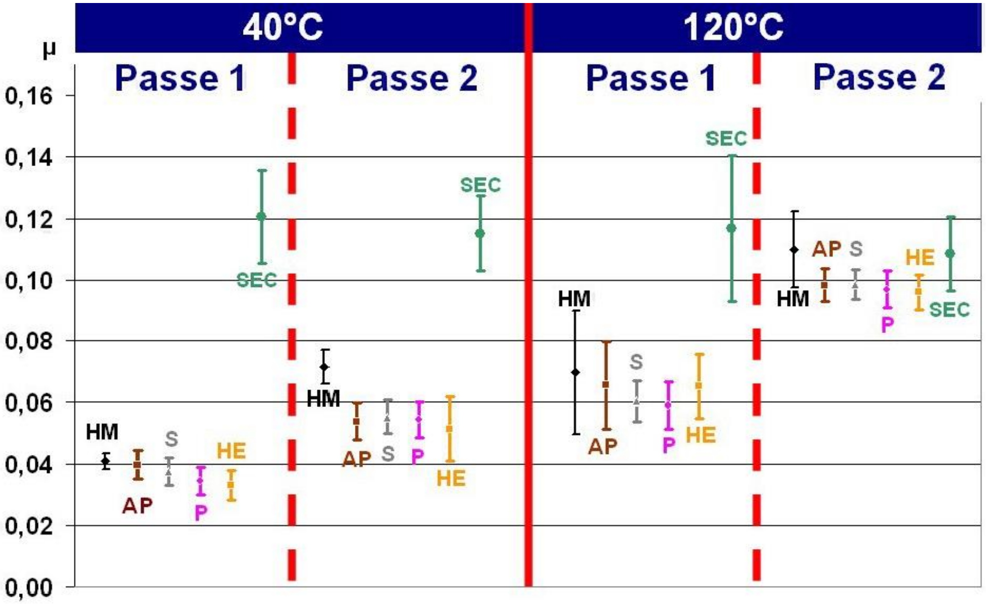


Effect of strip reduction (passe1: first reduction 28%, passe2: second reduction 28%), forward slip (2% or 7%) and roll temperature on the coefficient of friction

Some applications

1 **Testing of lubricants in cold rolling**

Testing of liquid lubricant. Effect of lubricant additives on surface protection.



HM: mineral oil
AP: HM + active polar additive
S: AP + sulfur based additive
P: AP + phosphorus based additive
HE: commercial oil

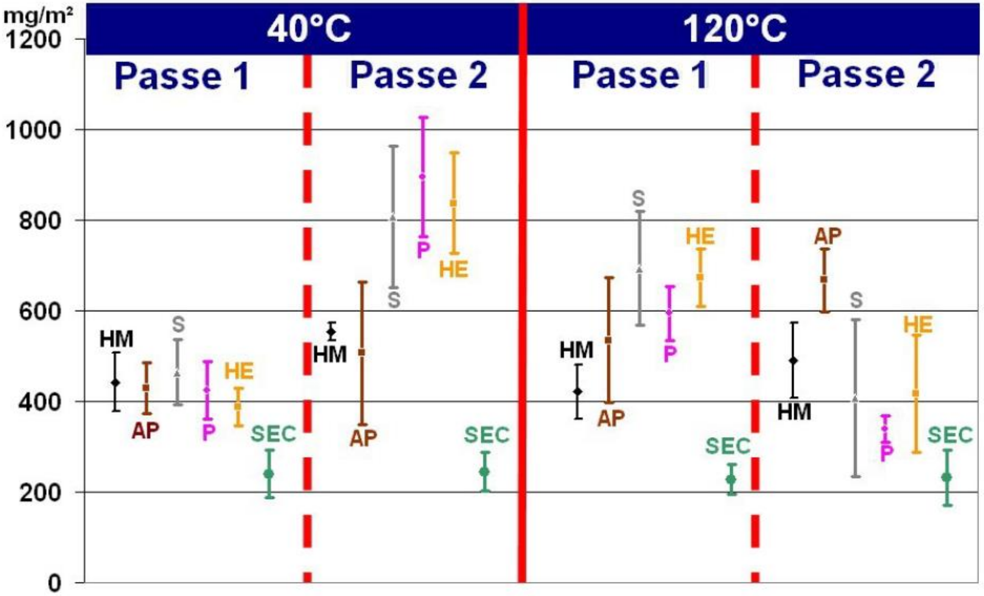
SEC: without lubricant

Effect of strip reduction (passe1: first reduction 28%, passe2: second reduction 28%), forward slip (2% or 7%) and roll temperature on the coefficient of friction

Some applications

1 **Testing of lubricants in cold rolling**

Testing of liquid lubricant. Effect of lubricant additives on surface protection.



HM: mineral oil
AP: HM + active polar additive
S: AP + sulfur based additive
P: AP + phosphorus based additive
HE: commercial oil

Effect of strip reduction (passe1: first reduction 28%, passe2: second reduction 28%), forward slip (2% or 7%) and roll temperature on ***strip cleanliness***

Some applications

1 Testing of lubricants in cold and hot forging

Conclusion application 1.

- Reliability of test results relies on the respect of real conditions of contact: plastic strain, contact pressure, thickness, viscosity and concentration of lubricants, tool temperature.
- Identifying coefficients related to various friction model provide information on lubrication regimes
- Coulomb's friction law is not efficient to predict friction stress in metal forming
- Nonetheless, Coulomb's friction coefficient remains a good indicator to quantify the evolution of the tribosystem

Some applications

2 Tool wear

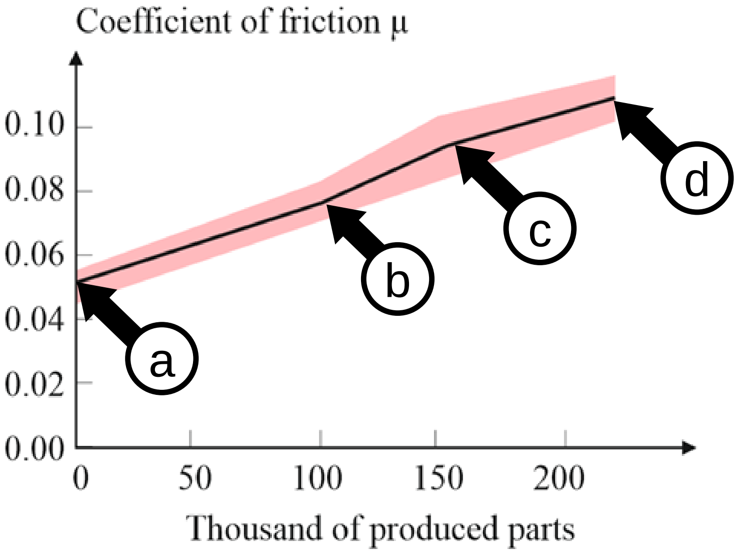
Cold forging dies a screw head. WC-Co wear mechanisms.

- Testing conditions:
  - Test Bench: Upsetting sliding Tests
  - Specimens: 21B3 steel
  - Contactors machined in industrial G30 WC-Co extrusion dies which have produced
    - **0, 100, 150 and 220 thousands of parts**
  - Contact pressure = 2.3 GPa
  - Plastic strain = 3
  - Sliding velocity = 60 mm.s^{-1}
  - Coefficient of friction identified after a sliding length of 20 mm.

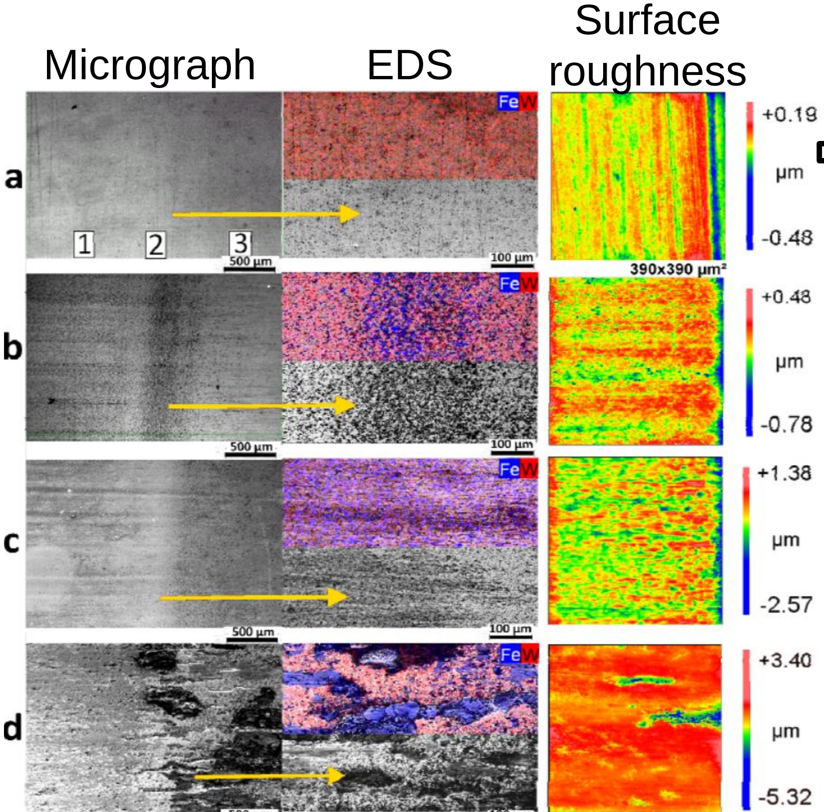
Some applications

2 Tool wear

Cold forging dies a screw head. WC-Co wear mechanisms.



Linear increase of the coefficient of friction



Fracture of WC grains

WC Grain removal

Adhesive wear

Some applications

2 Tool wear

Cold forging dies a screw head. PVD vs CVD.

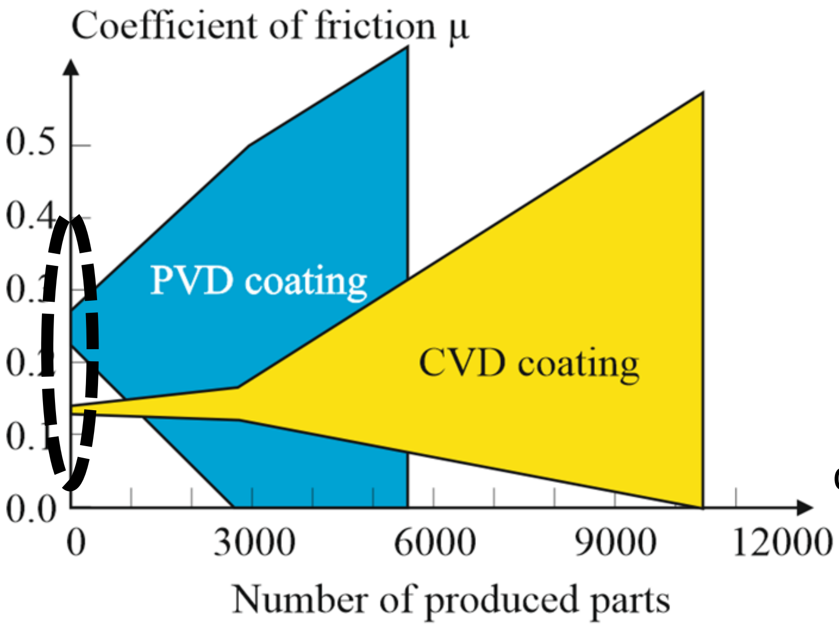
- Testing conditions:
  - Test Bench: Upsetting sliding Tests
  - Specimens: 21B3 steel
  - Contactors machined in industrial TiN coated AISI M2 dies which have produced
    - **0, 3000 and 6500 parts for the PVD coatings**
    - **0, 3000 and 11400 parts for the CVD coatings**
  - Contact pressure = 2.3 GPa
  - Plastic strain = 3
  - Sliding velocity = 60 $mm.s^{-1}$
  - Coefficient of friction identified after a sliding length of 20 mm.

Some applications

2 **Tool wear**

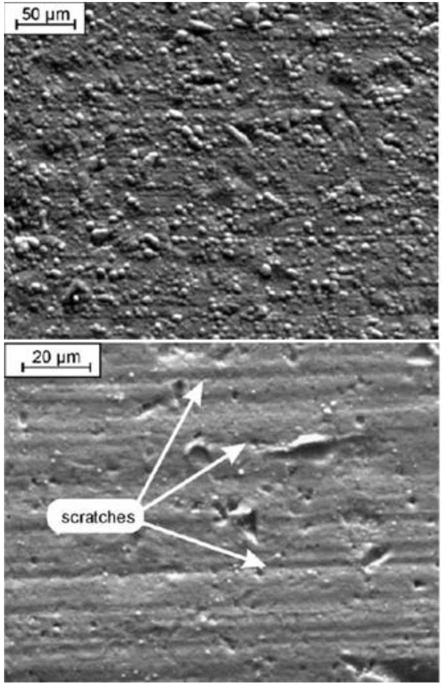
Cold forging dies a screw head. PVD vs CVD.

- Discrepancies of friction with number of produced parts:



CVD coating

PVD coating



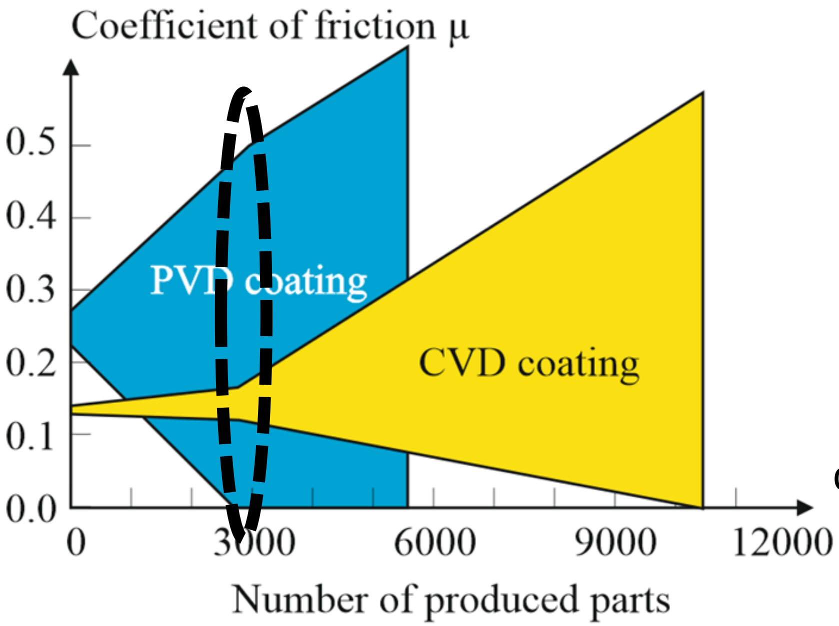
- Small spheres on surface
- Machining grooves still appears through the TiN coating

Some applications

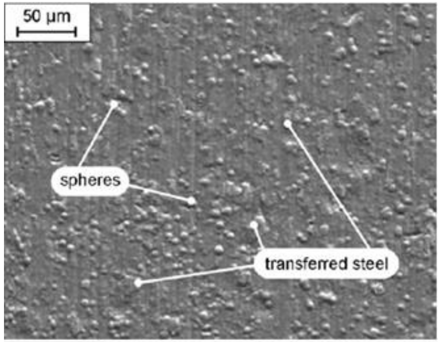
2 **Tool wear**

Cold forging dies a screw head. PVD vs CVD.

- Discrepancies of friction with number of produced parts:

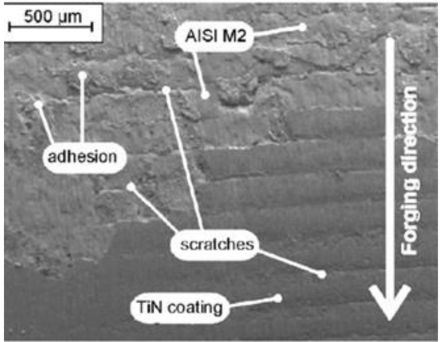


CVD coating



- Adhesive wear appears around the spheres

PVD coating



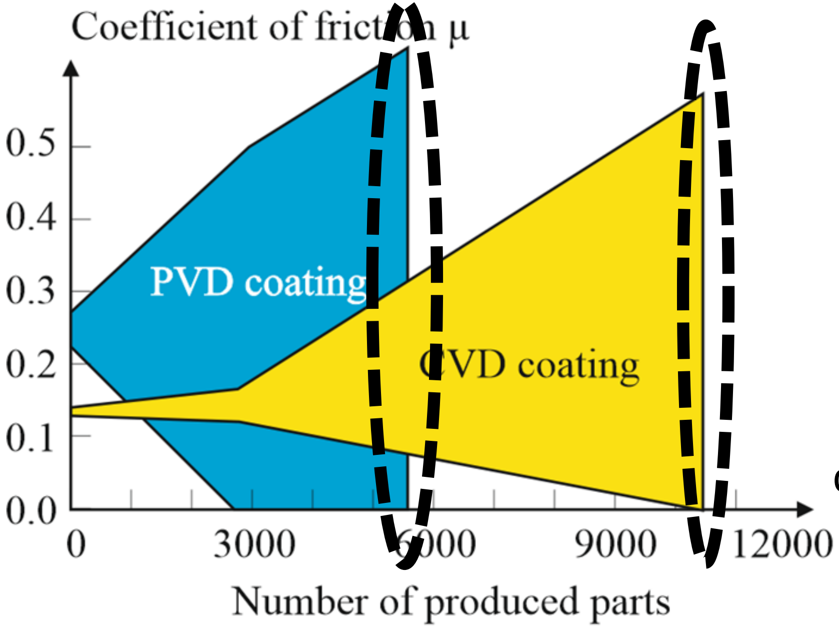
- Large cracks along the machining grooves. Adhesive wear.

Some applications

2 **Tool wear**

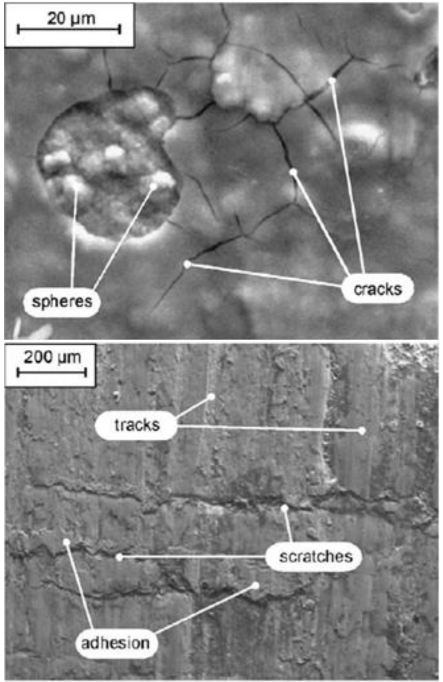
Cold forging dies a screw head. PVD vs CVD.

- Discrepancies of friction with number of produced parts:



CVD coating

PVD coating



- Chips removal caused by contact fatigue
- Adhesive wear along the scratches + abrasive wear

Some applications

2 Tool wear

Conclusion 2.

- Working on industrial tools taken at different production time leads to an accurate and reliable view of wear evolution
- UST are then able to quantify the wear effect on friction. Here again, Coulomb's friction coefficient remains a good indicator to quantify the evolution of the tribosystem
- Tool surface is subjected to various kinds of wear at the same time: adhesive, abrasive and contact fatigue. Wear studies conducted with a common pin-on-disk tribometer hardly reproduce these specificities.

Some applications

3 Modelling of mixed lubrication

Main objective: control strip brightness in cold rolling of stainless steel by predicting its final roughness

Main questions to be solved were:

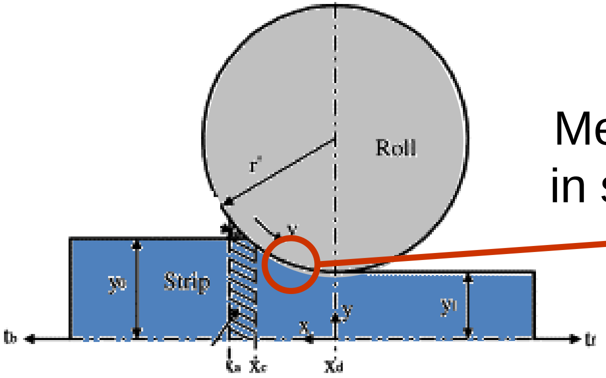
- Fluid/solid interaction: which method should we used? Strong or weak coupling?
- How to manage the different scales from the process to the asperities in contact?
- 2D or 3D analyses?

- **How to validate the models?**

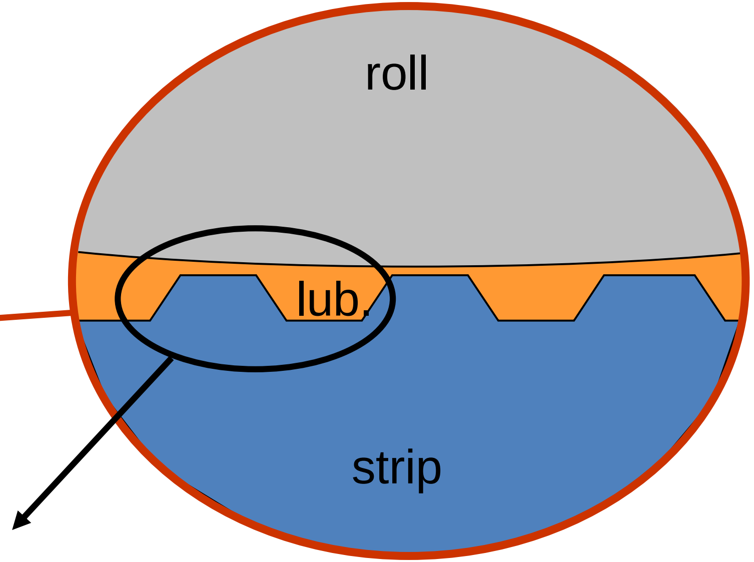
Some applications

3 **Modelling of mixed lubrication**

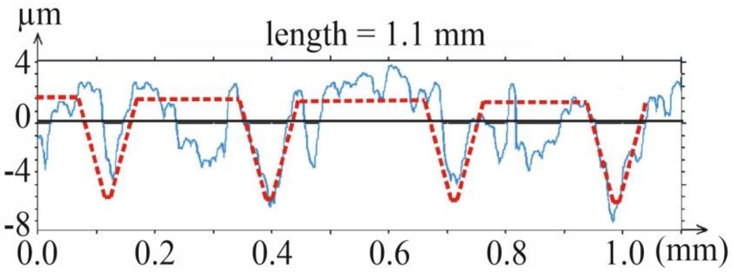
Proposed methodology:



Mesh refinement in surface vicinity



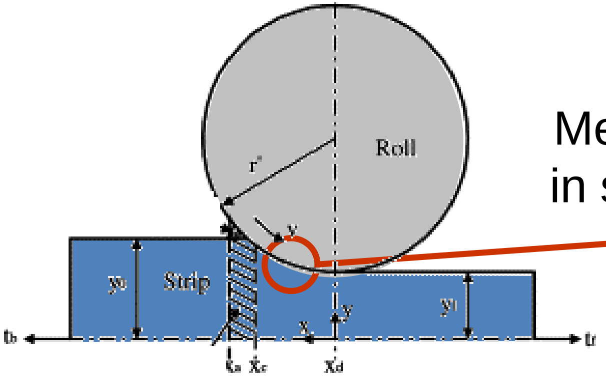
Geometry of asperities based on real surface roughness



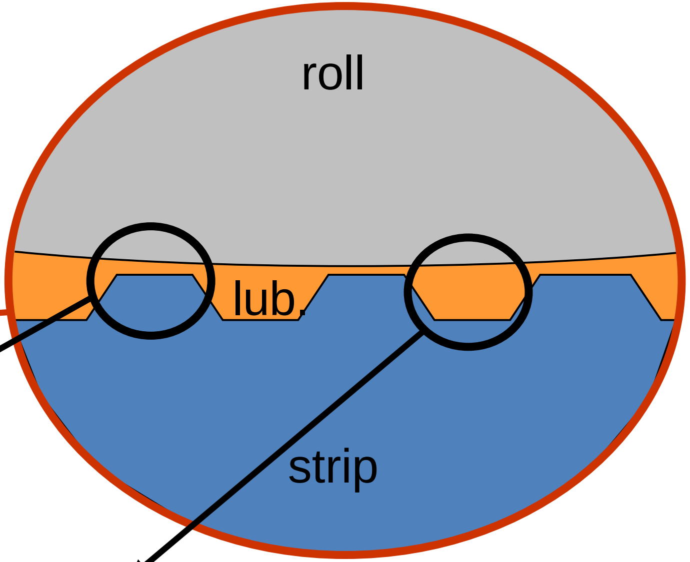
Some applications

3 Modelling of mixed lubrication

Proposed methodology:



Mesh refinement in surface vicinity



- Solid computation:
  - ABAQUS FE software
  - Strip: elastoplastic behaviour
  - Rigid working roll
  - Coulomb's friction law

- Fluid flow
  - Reynolds equations solved with Matlab

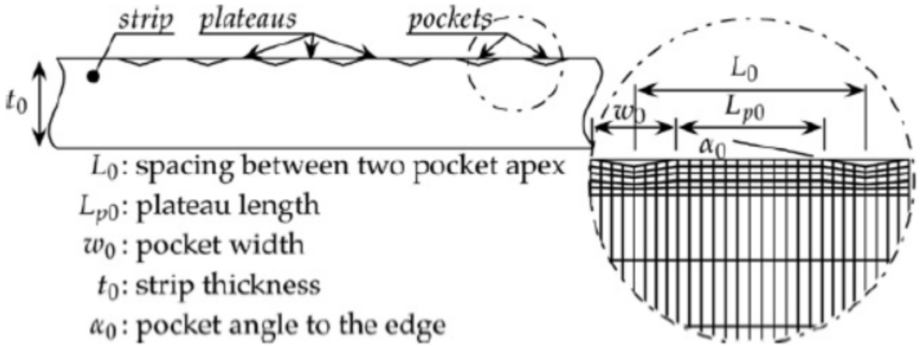
$$\frac{d}{dx}\left(\Phi_x \frac{h_t^3}{12\eta}\frac{dp_f}{dx}\right) = -\Phi_{ux}\left(\frac{u_r + u_w}{2}\frac{dh_t}{dx} + \frac{h_t}{2}\frac{du_w}{dx}\right)$$

Some applications

3 Modelling of mixed lubrication

Validation: strip drawing test with “macro roughness”

Numerical simulation



Experiments

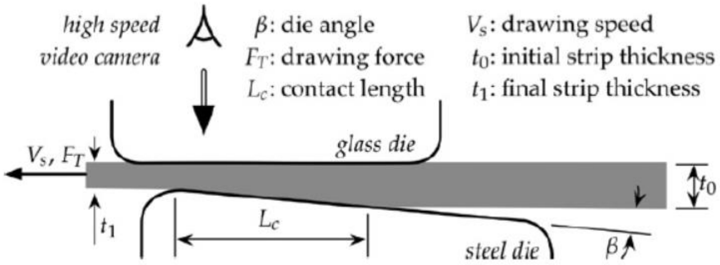
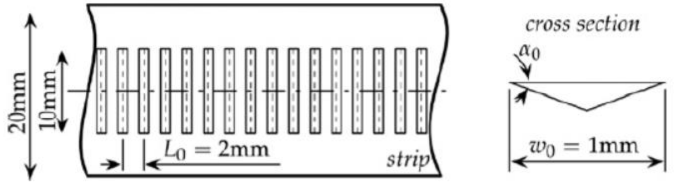


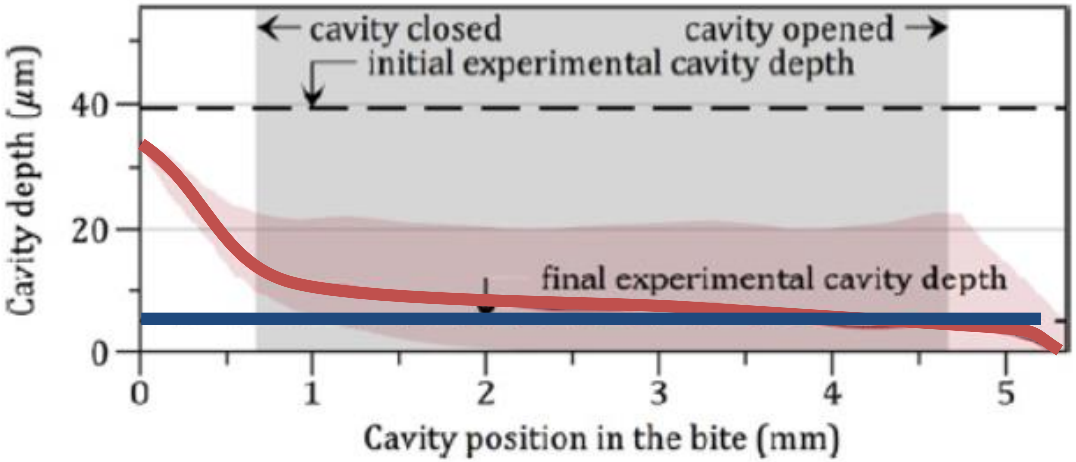
Fig. 3. Schema of the experimental testing device.



Some applications

3 **Modelling of mixed lubrication**

Validation: strip drawing test with “macro roughness”



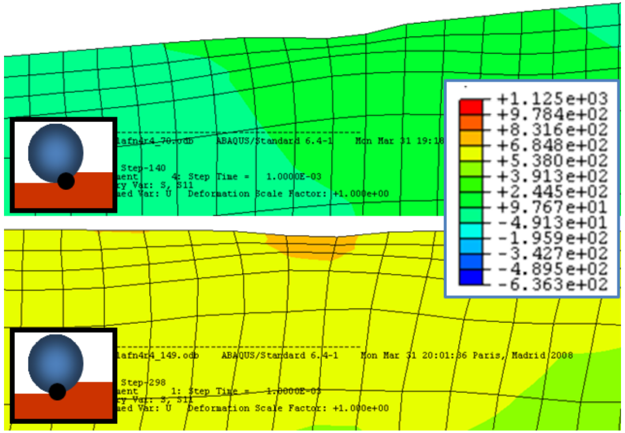
- Good correlation between experimental and numerical final depth of asperities.

Some applications

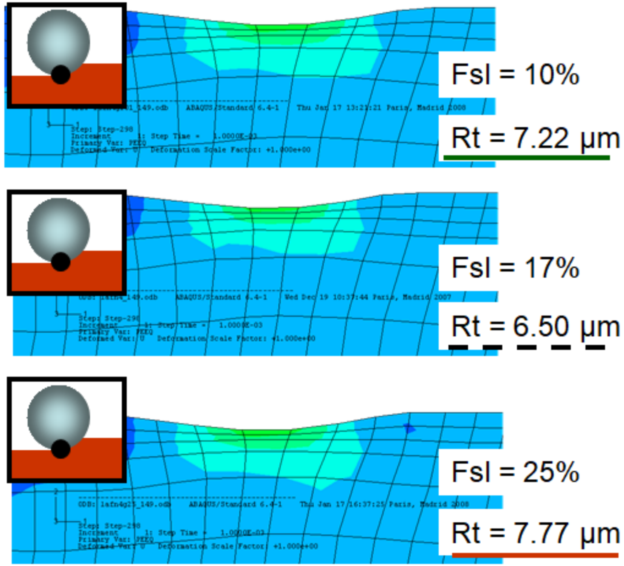
3 Modelling of mixed lubrication

Some results related to cold rolling:

- the valleys are subjected to tensile stresses although the strip is mainly in compression



- Position of the neutral point affect the final roughness (geometry and height)



3 Modelling of mixed lubrication

Conclusion 3.

- The weak fluid/solid coupling provide results in good agreement with experiments
- Final roughness is affected by process parameters
- Proposed methodology is limited to 2D roughness profile (Reynolds equations)

Some applications

4 Cleanliness

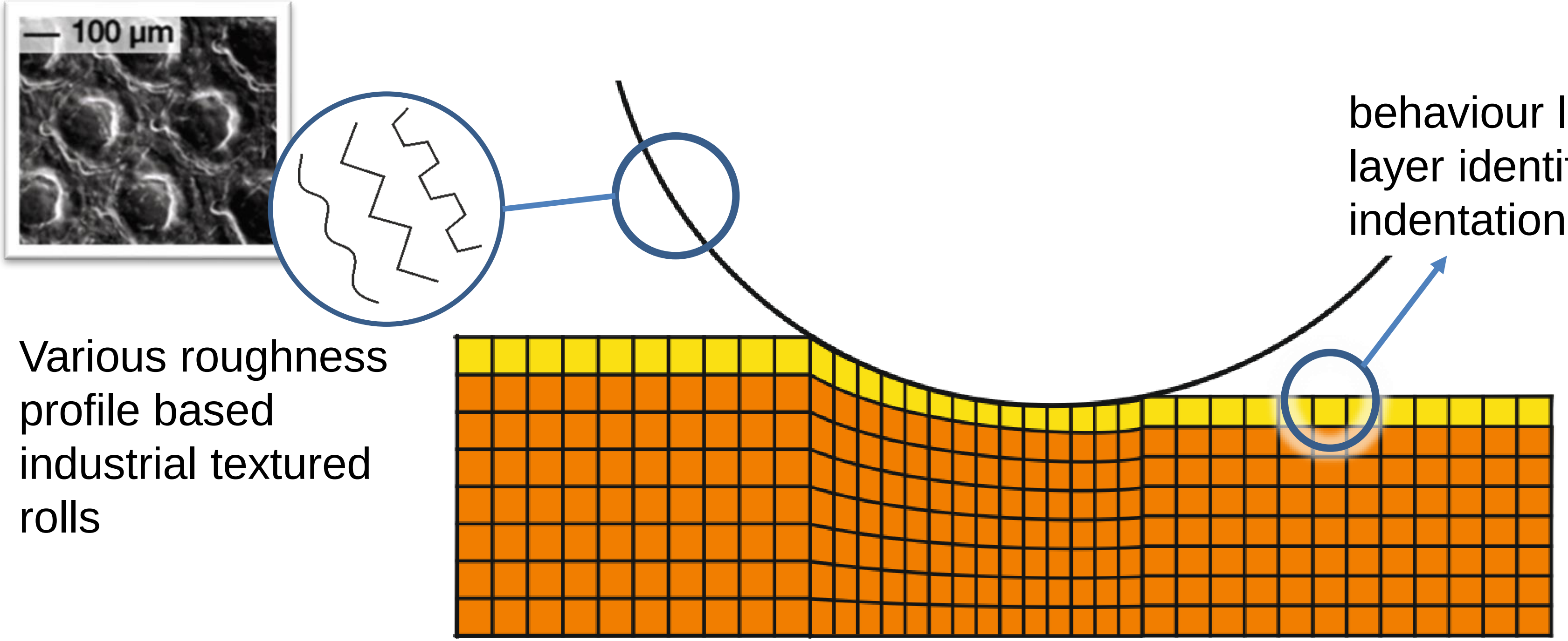
Main objective: Prediction of zinc fine formation in the cold rolling of galvanized steel strip (skin pass).

Methodology:

- 2D Finite element analyses of the skin-pass process
- Modeling of roll roughness
- Modelling of the zinc layer
- Use of Griffith’s and Lemaitre’s models to predict zinc tearing from the strip surface
- Process:
  - strip reduction of 1 or 2%
  - no lubricant

Some applications

4 Cleanliness



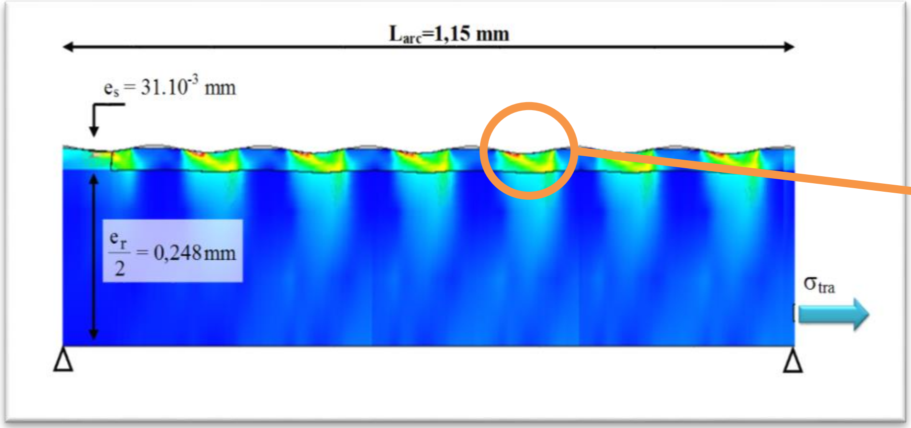
Various roughness profile based industrial textured rolls

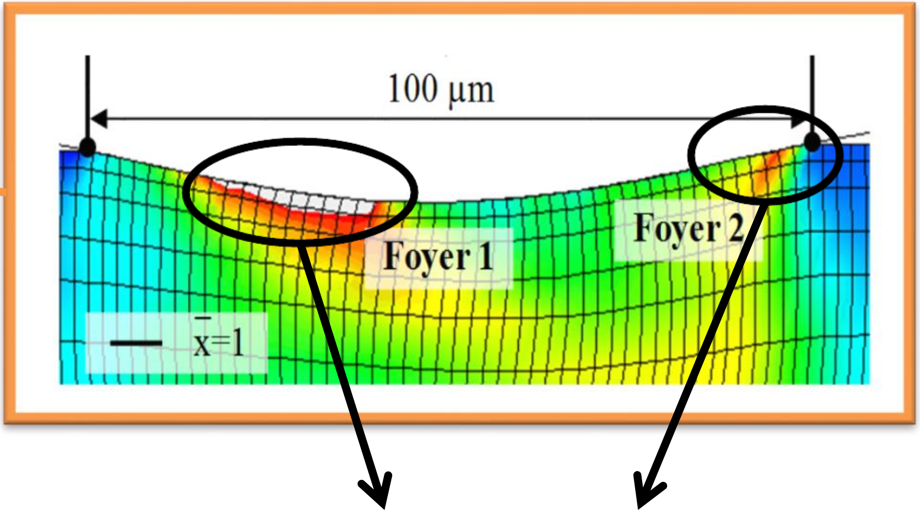
behaviour law of zinc layer identified from indentation tests

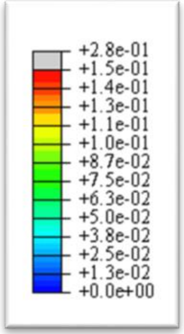
Some applications

4 **Cleanliness**

Results: sinusoidal asperity profile







Deformed mesh

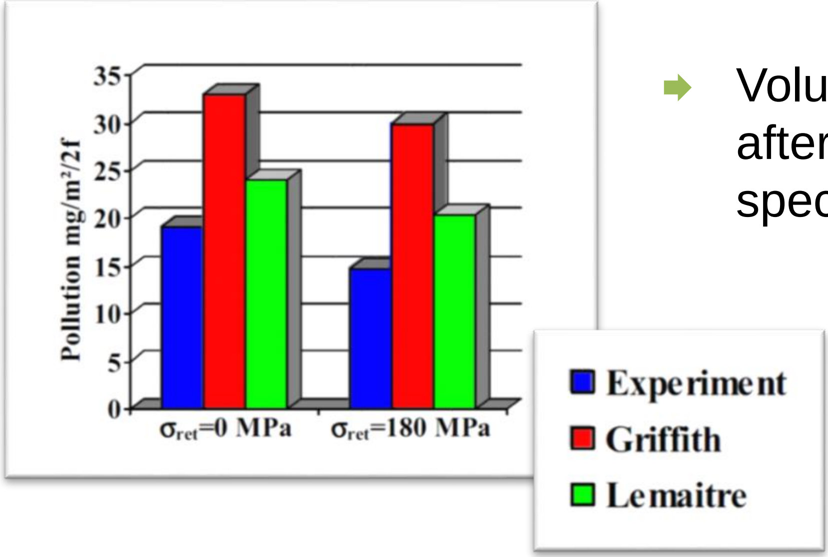
Critical zones where damage is maximum

➡ **Volume of zinc fines torn from strip surface**

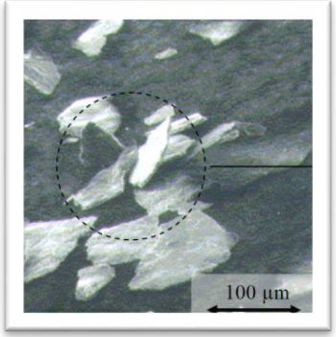
Some applications ❹ Cleanliness

Results: sinusoidal asperity profile

- Comparison between Lemaitre's and Griffith's models



- Volume of zinc fines measured after friction tests by mass spectroscopy

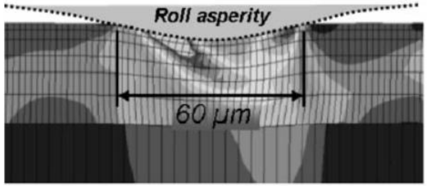


- Good correlation with experiments
- Lemaitre's damage model more accurate than Griffith fracture model

Some applications

4 Cleanliness

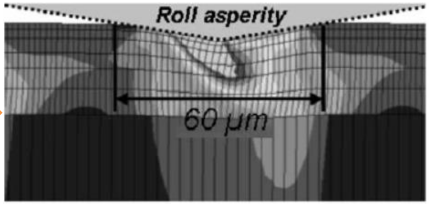
Results: sinusoidal vs triangular and trapezoidal profiles



Sinusoidal profile

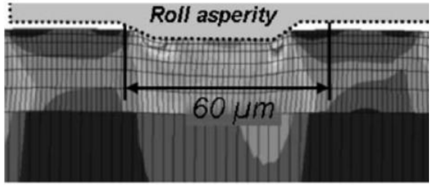
→ 5 $mg.m^{-2}$

FEM analyses of the skin pass process with various roll profiles ⇨



Triangular profile

→ 16 $mg.m^{-2}$ ⇨ **Sinusoidal profile should lead to the lower surface pollution**



Trapezoidal profile

→ 9 $mg.m^{-2}$

Prediction of zinc fine volume with Lemaitre's damage model

Some applications

4 Cleanliness

Conclusion 4.

- Good correlation between numerical simulation and experiments although the strong assumptions of the numerical model *(2D roughness, material is broken when Dc = 0.7, predicted volume of zinc fine = 100% of the damaged material…)*

- Possibility to test various roll profiles without expensive manufacturing of textured rolls

Conclusion

- Along the years…
  - Development of test benches dedicated to « extreme conditions of contact »: high contact pressure, high temperature, high sliding speed,
  - Development of methodologies that allow test benches to respect the tribology of forming processes: respect of the materials in contact, of the mechanical and thermal loadings,
  - Results based on the coupling between experiments, numerical simulations and surface analyses,
  - Application to various processes (cold and hot, with sliding or rolling contact).

Conclusion

- Many results:
  - Procedure for the choice of lubricants in cold and hot forging, in cold rolling
  - Testing of tool wear: WC-Co and TiN coatings in cold forging, development of sol-gel coatings for hot forging tool,
  - Process improvement: strip cleanliness in skin pass process, strip brightness in cold rolling,
  - Increase of scientific knowledge: analysis of fluid lubrication mechanisms at mesoscopic scale, dynamic recrystallization behaviour of spheroidal graphite iron in machining conditions…

Thank you for your attention

Tribology under extreme conditions devoted to manufacturing processes: methods and approaches developed at LAMIH

Laurent **Dubar**, André **Dubois**, Mirentxu **Dubar**

Réunion de la Commission Thématique Laminage de la SF2M
Meeting of the thematic group "rolling processes" of the French Society of metallurgy and materials