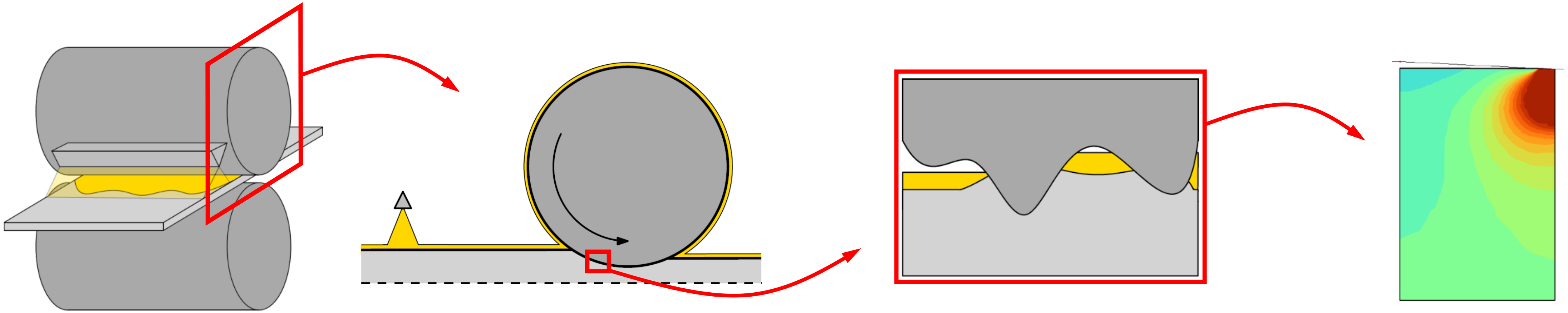
Coupling Procedure of a Cold Rolling Lubrication Model with Finite Element Simulation of Asperity Flattening



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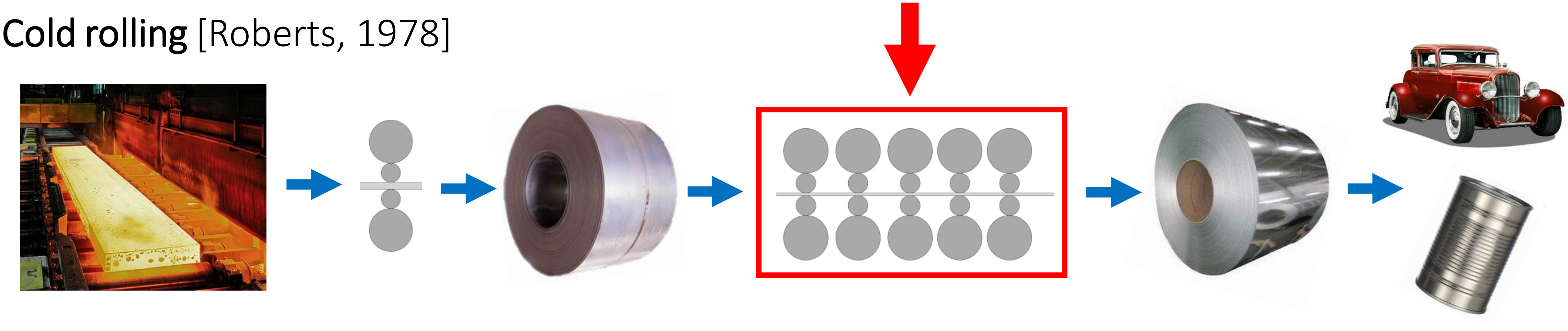
Outline

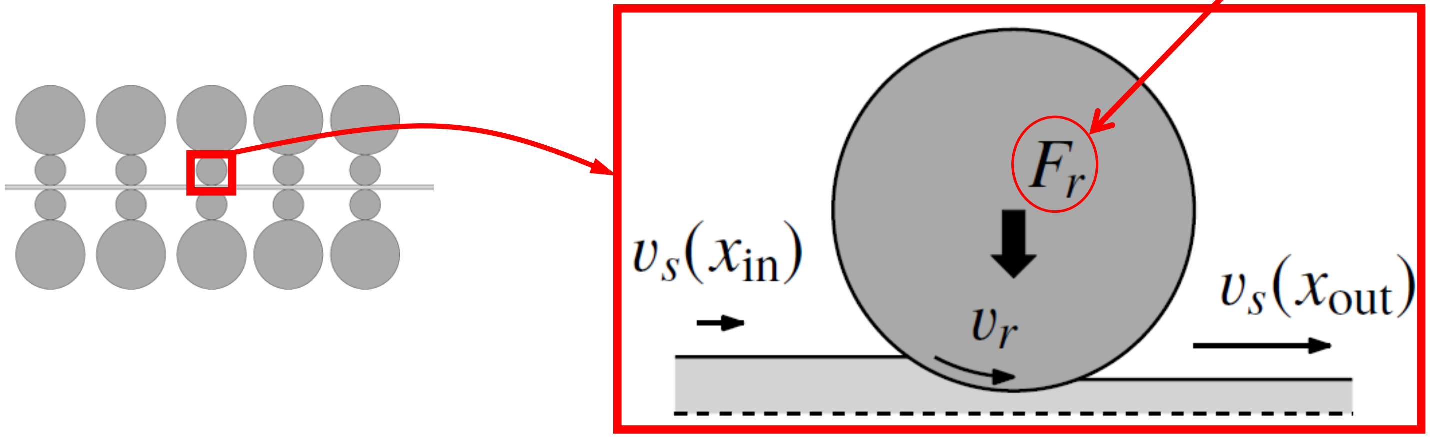
1. Context
2. Metalub
3. Metalub – Metafor coupling
4. Conclusion

1. Context

Cold rolling [Roberts, 1978]



- Thickness reduction of steel strips at 25 - 150°C to satisfy strict geometrical tolerances
- Process is strongly dependent on friction created by speed difference between roll and strip
- Friction increases important process parameters like the rolling force and the forward slip

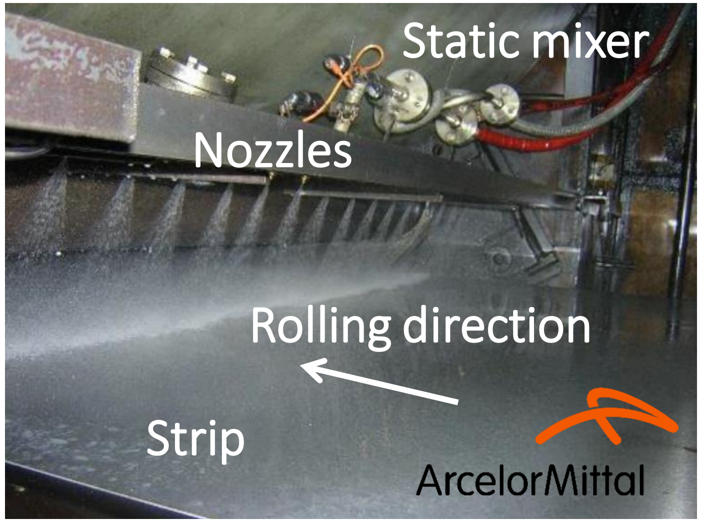


$$S_F = \frac{v_s(x_{out}) - v_r}{v_r}$$

Mixed lubrication

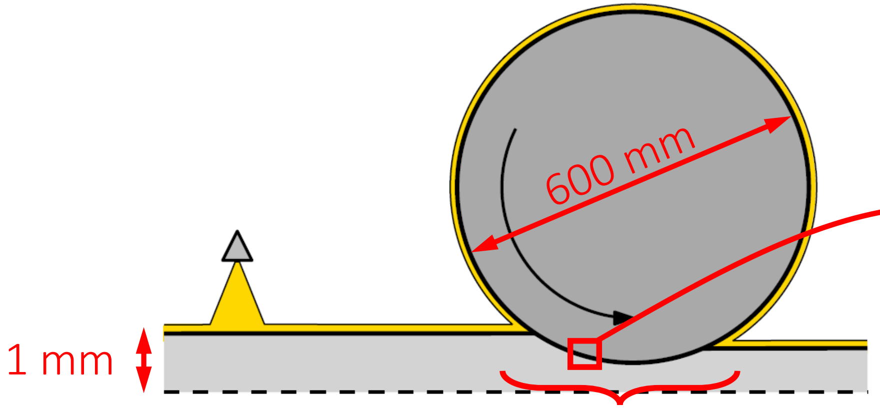
- Challenges due to friction:
  - Mill capacity for Advanced High-Strength Steel (harder, thinner)
  - Rolling energy consumption
  - …

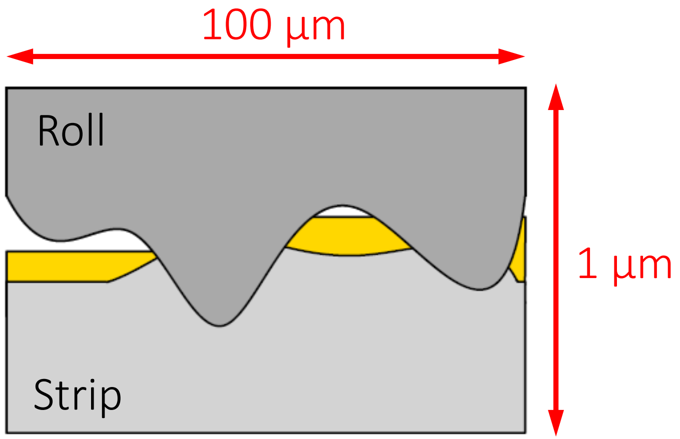
- Introduction of a lubricant, and more recently, flexible lubrication
  - Control of friction level by adjusting oil concentration in emulsion



[Laugier et al., 2011]

- Interacting solid asperity tops in the presence of a lubricant, which partially supports the load

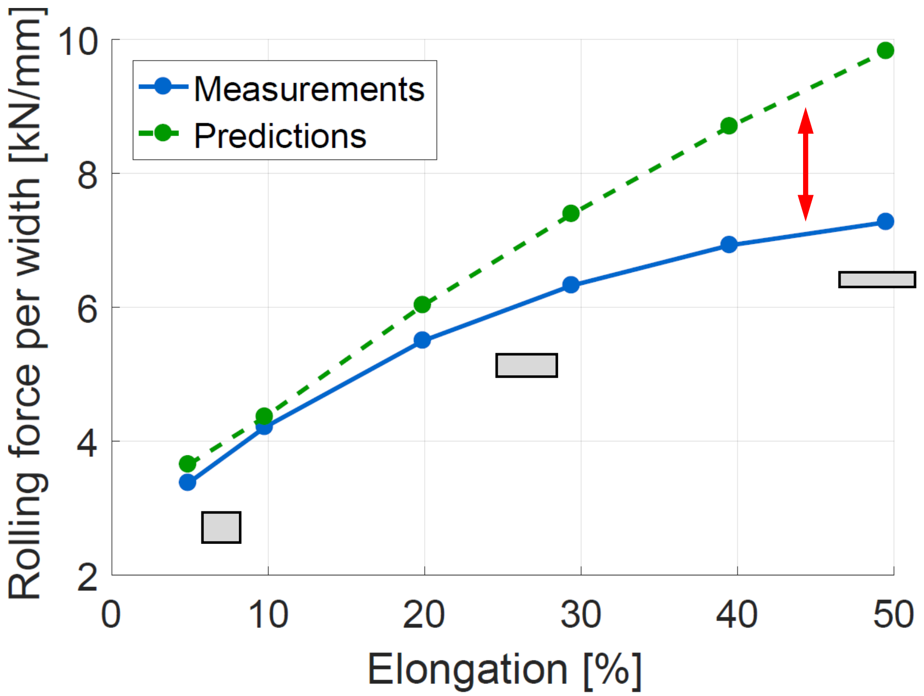


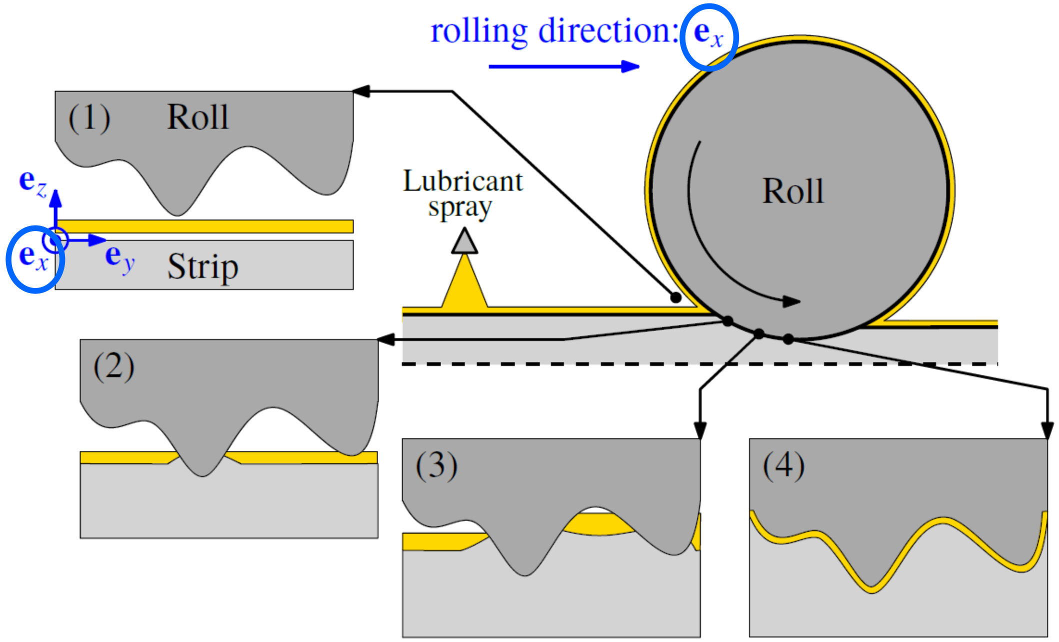


1. Context

Motivation

- Predict rolling force and forward slip numerically
- To minimize friction by choosing optimal process parameters
  - Include micro-plasto-hydrodynamic and hydrostatic effects [Laugier et al., 2014] in the model





- This talk: coupling of cold rolling model with the finite element (FE) simulation of asperity flattening

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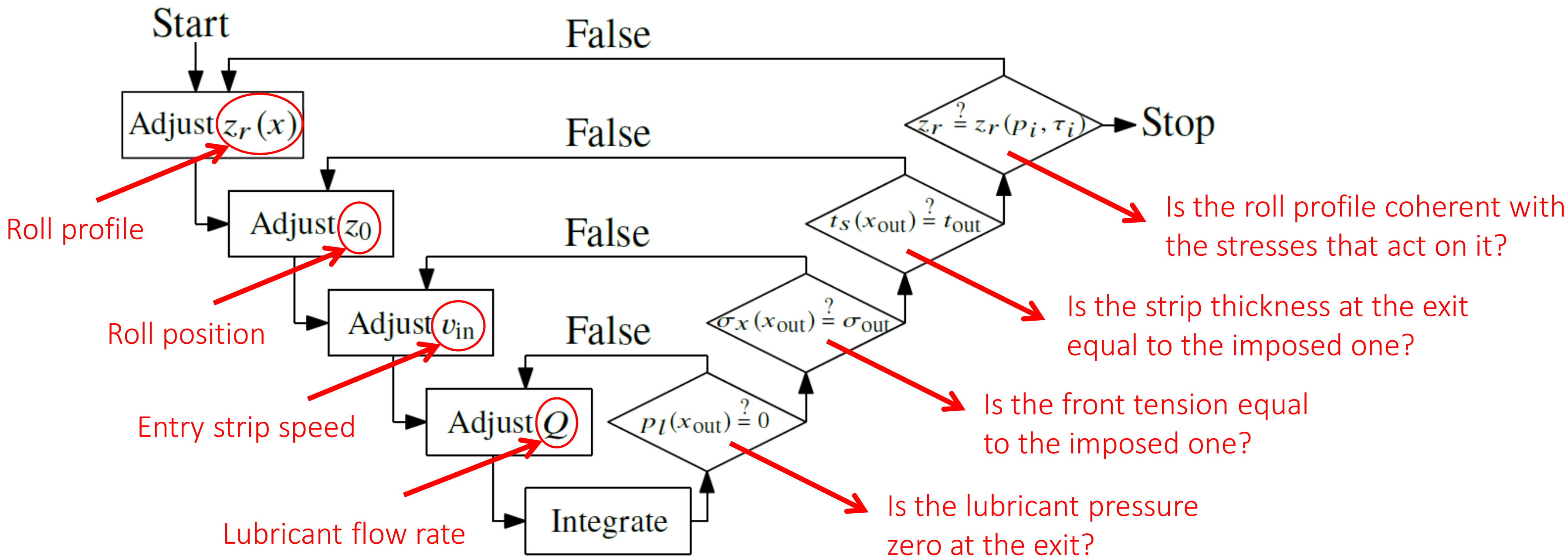
2. Metalub

Cold rolling model with mixed lubrication

- Over 20 years of development: [Marsault, 1998], [Boman et al., 2002], [Stephany, 2008], [Carretta, 2014]
- Numerous features:
  - Conservation laws: slab method, adiabatic thermal model, Reynolds equation with flow factors
  - Material laws: thermoviscoplastic (strip), thermopiezoviscous (lubricant)
  - Additional features: non-circular elastic roll flattening, lubricant starvation
  - Implemented in C++ with Python interface and GUI
- Method:

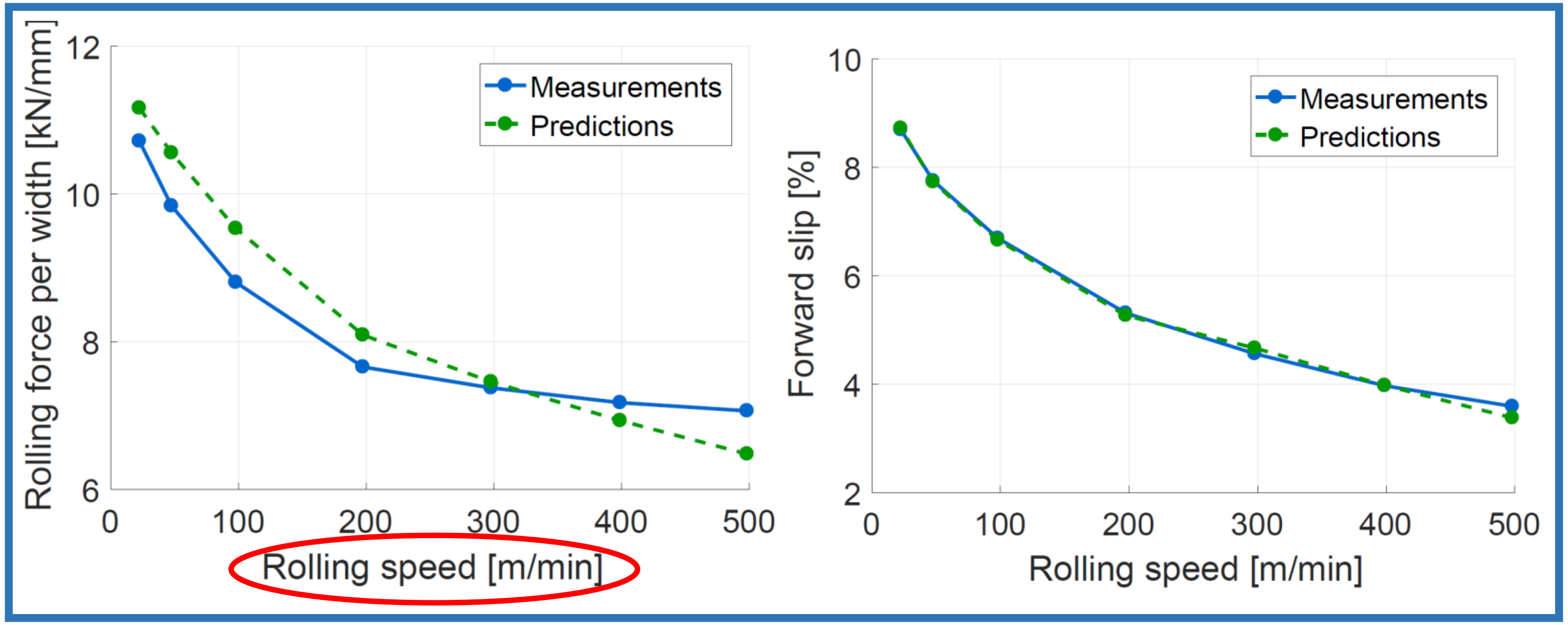


2. Metalub

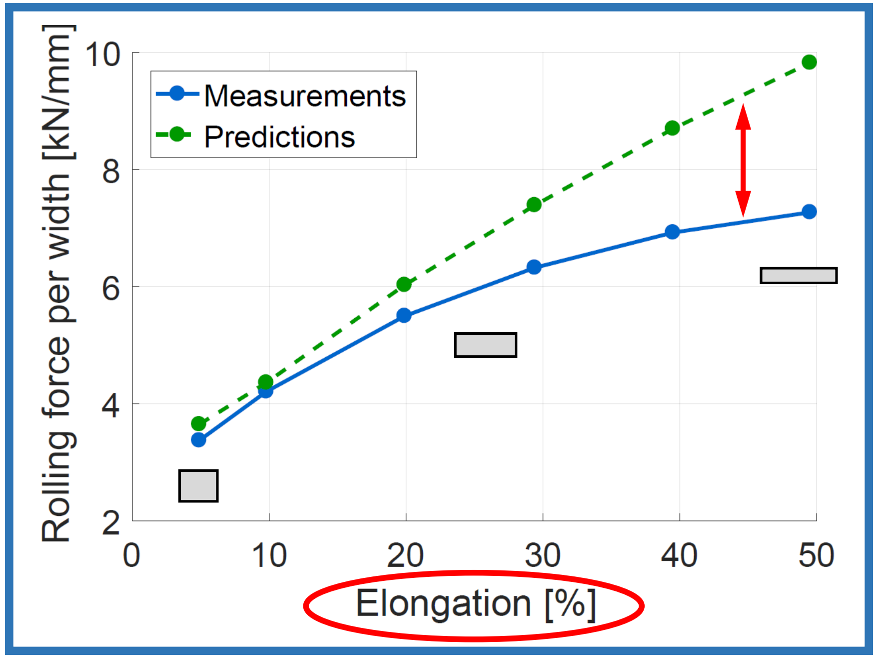
Numerical results

- Excellent predictions in some cases (scenario A)
- But more significant deviations in others (scenario B)
- With respect to measurements of pilot mill [Legrand et al., 2015]

Scenario A

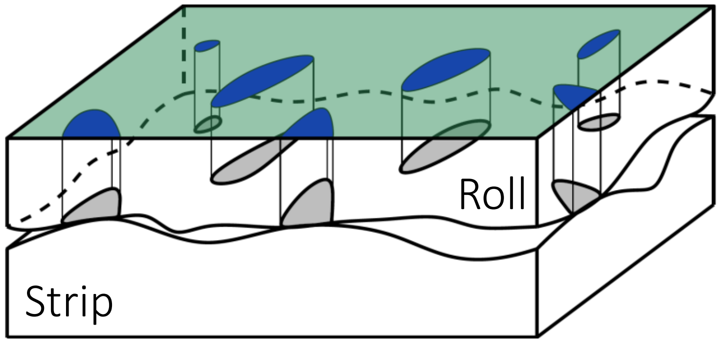


Scenario B



Analytic asperity flattening law

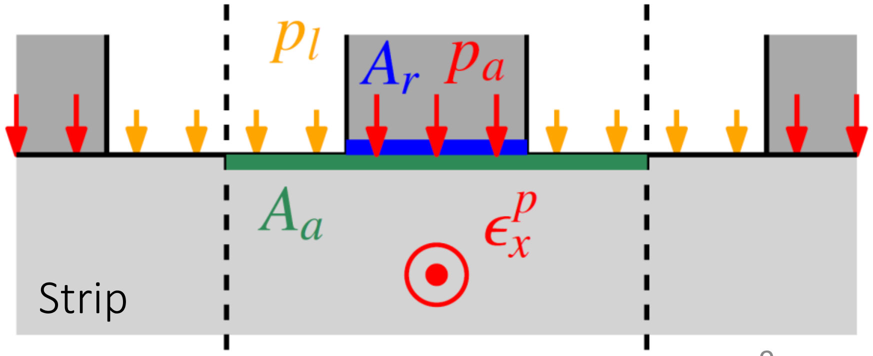
- Relation between:
  - Relative contact area $A = A_r / A_a$
  - Pressure on the asperity tops p_a
  - Lubricant pressure p_l
  - Plastic substrate deformation ϵ_x^p



- Currently implemented: Wilson & Sheu, Sutcliffe & Marsault, Korzekwa et al.

$$E_p = \frac{1}{0.515 + 0.345A - 0.860A^2}\left(\frac{2}{H_a} - \frac{1}{2.571 - A - A\ln(1-A)}\right) \quad \text{with} \quad \begin{aligned} E_p &= E_p(\dot{\epsilon}_x^p) \\ H_a &= H_a(p_a - p_b) \end{aligned}$$

- Shortcomings:
  - Simplified geometry: flat indenters
  - Simplified material law: rigid perfectly plastic
  - Approximate method: upper-bound method
  - No micro-plasto-hydrodynamic or hydrostatic effect



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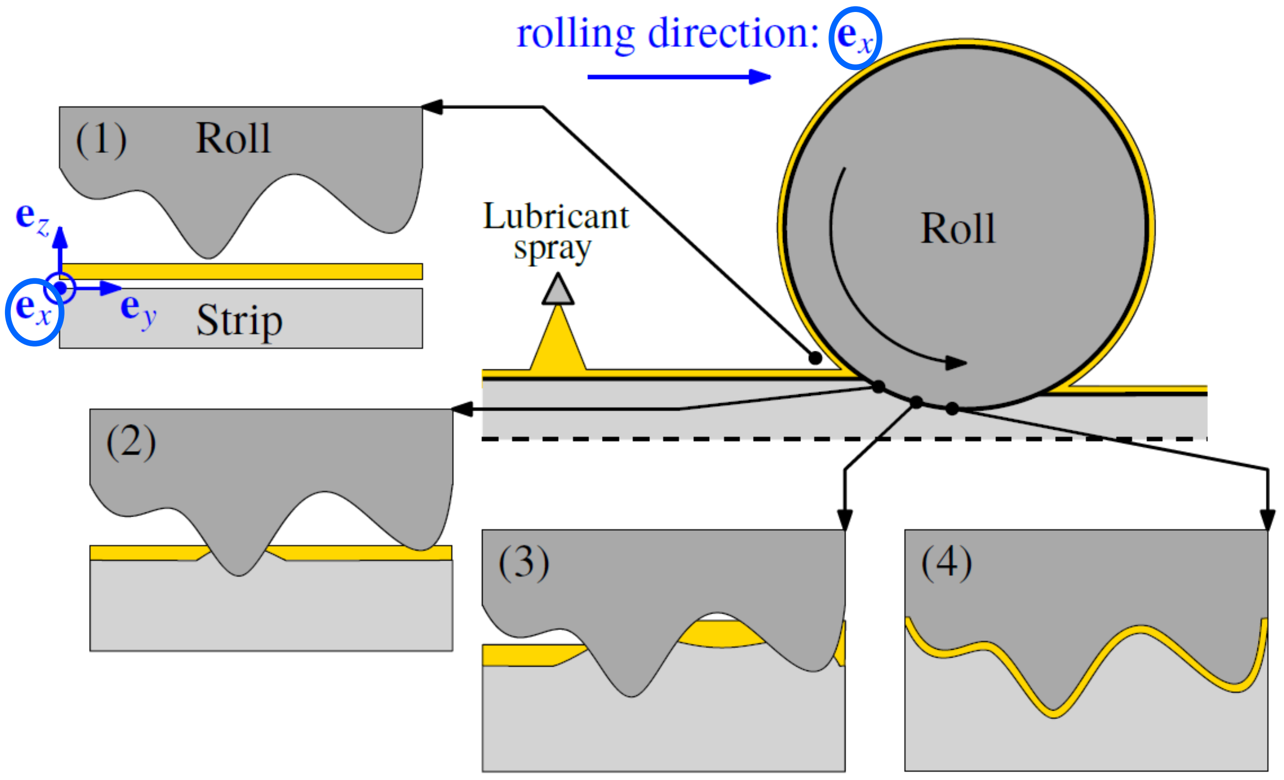
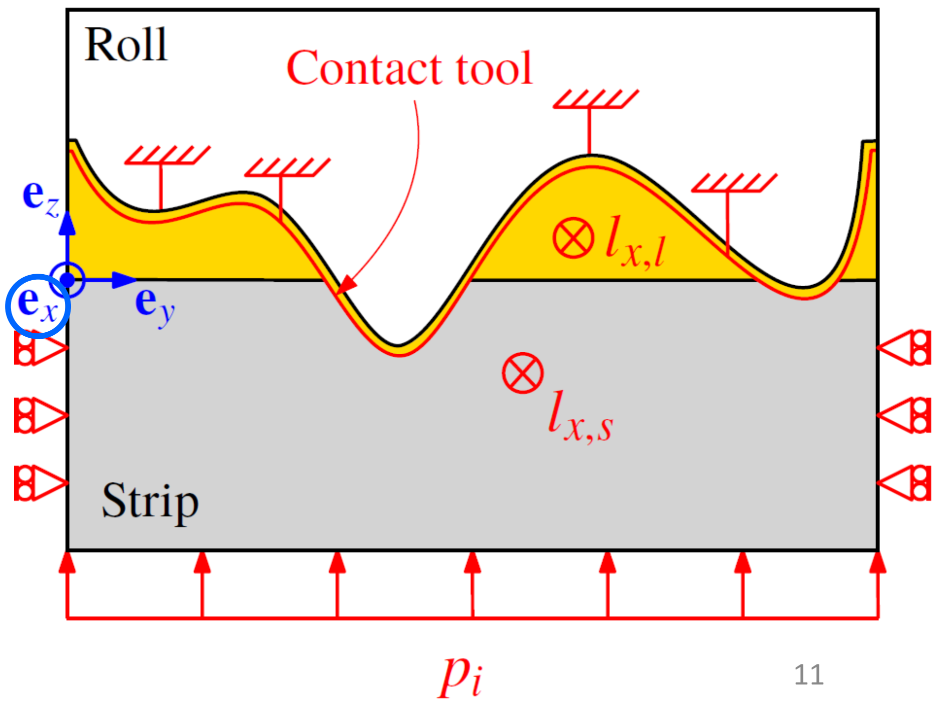
3. Metalub – Metafor coupling

Carretta's micro-model of asperity flattening with lubricant

- Metafor: in-house non-linear implicit FE solver for large deformations
- FE asperity flattening in normal plane to the rolling direction
- Direct simulation of lubricant by Arbitrary Lagrangian Eulerian formulation
  - Problematic due to co-existence of hydrostatic and hydrodynamic models



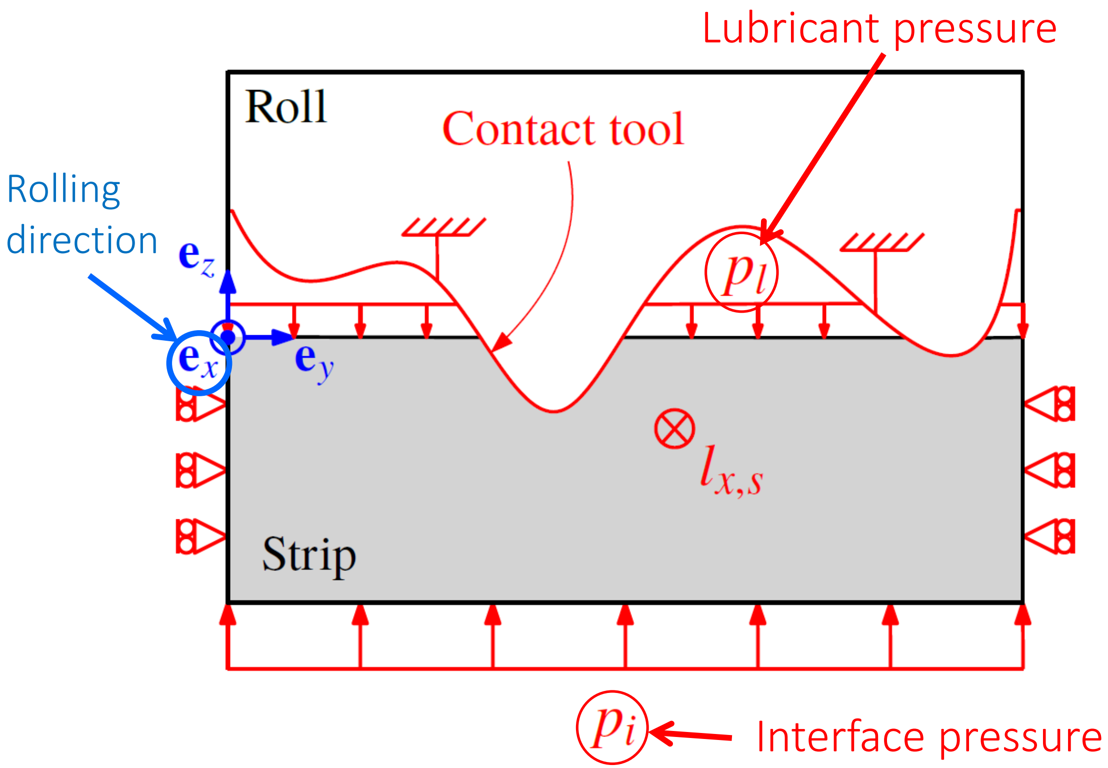


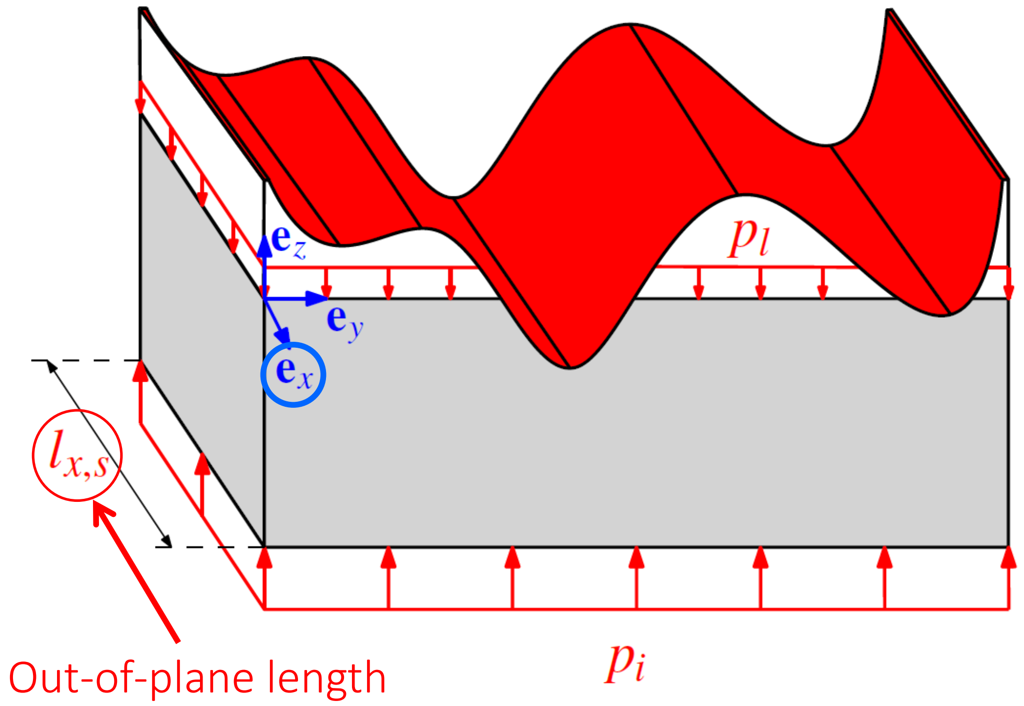
3. Metalub – Metafor coupling

New micro-model of asperity flattening

- Roll modeled by rigid fixed contact tool
- Strip modeled by FEM
- Interface pressure pushes strip against roll
- Strip can not deform laterally

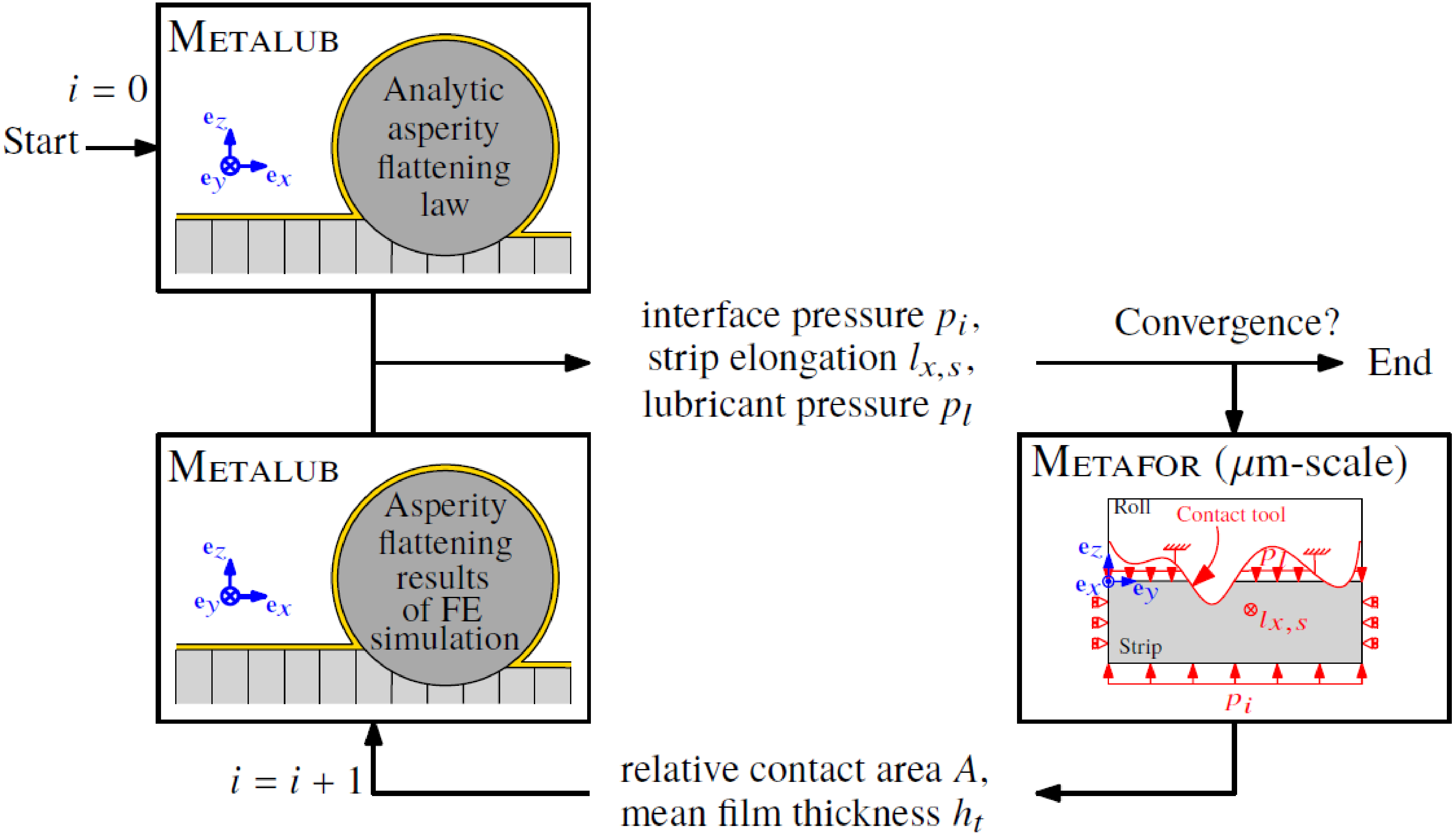
- Generalized plane strain state
  - Elongation of strip due to its deformation
- Lubricant pressure applied where no contact exists between roll and strip





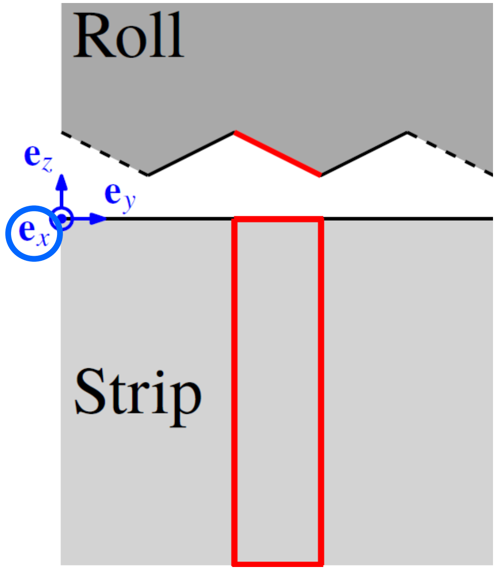
3. Metalub – Metafor coupling

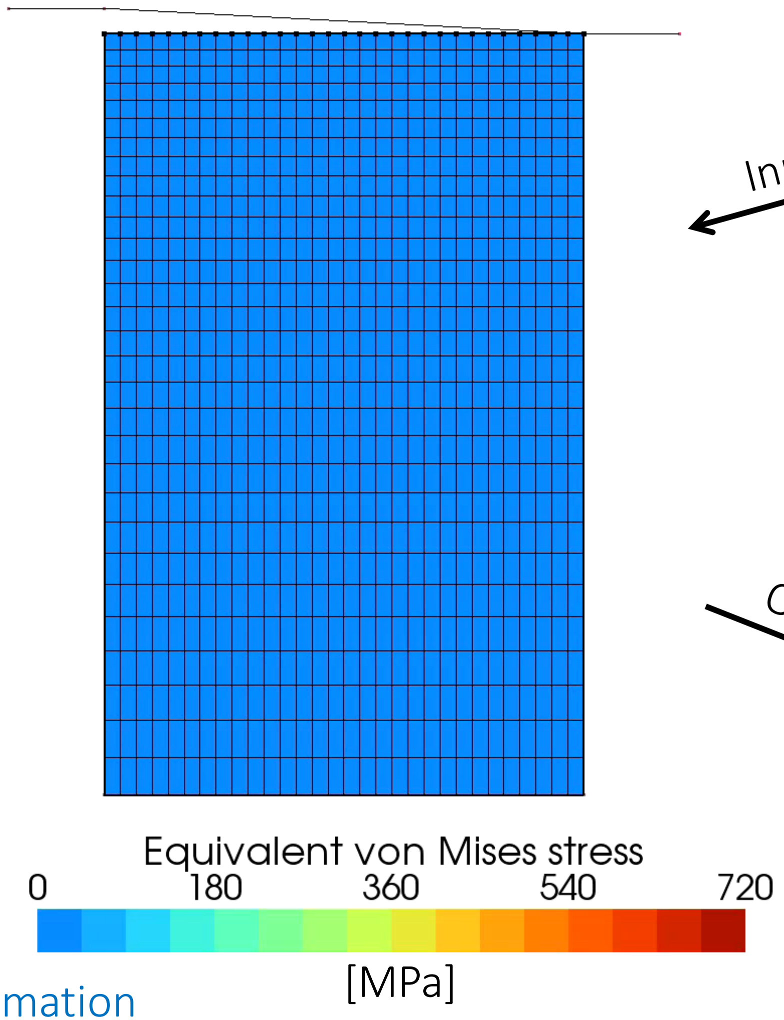
Full coupling procedure



3. Metalub – Metafor coupling

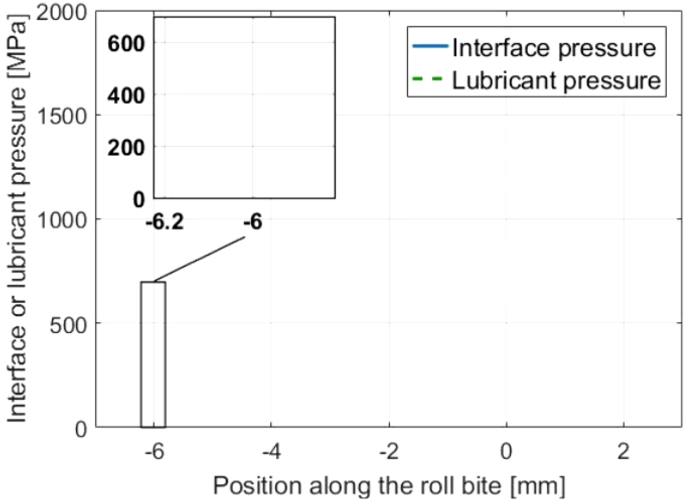
Numerical results (1)

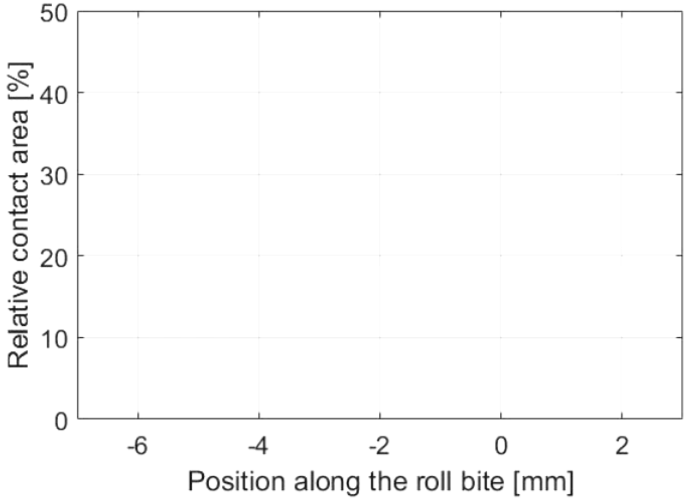




Input

Output

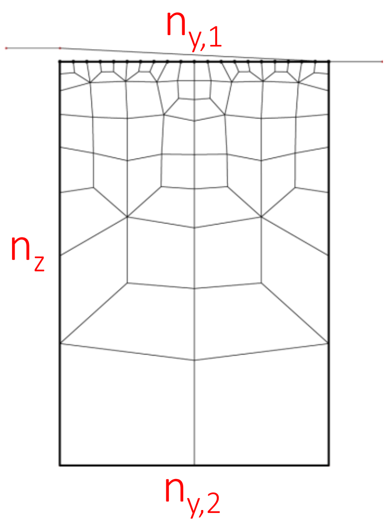


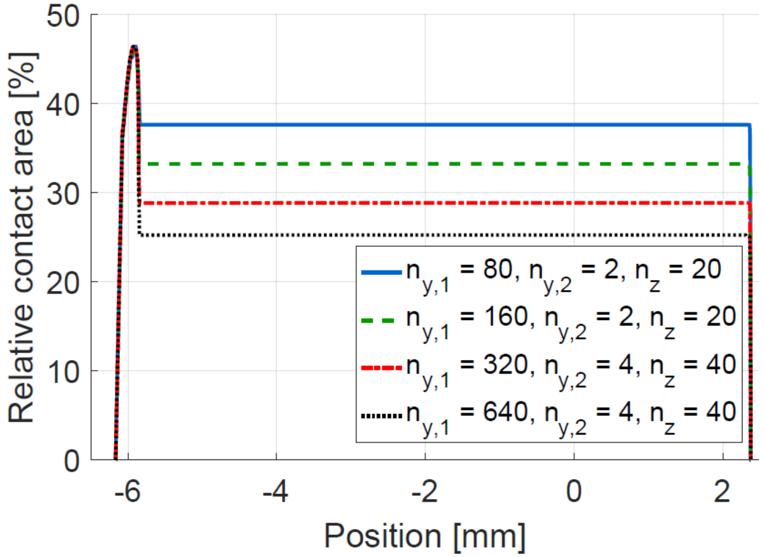


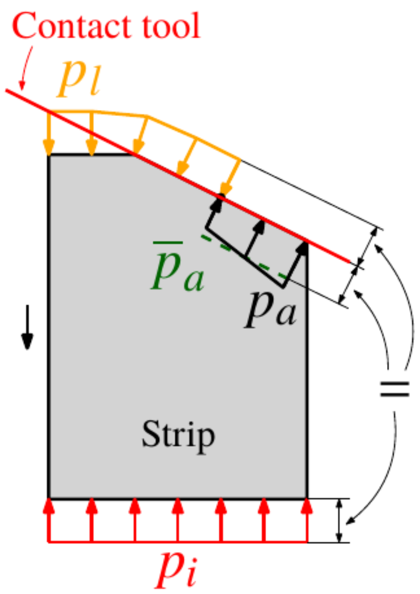
Animation

Shortcomings

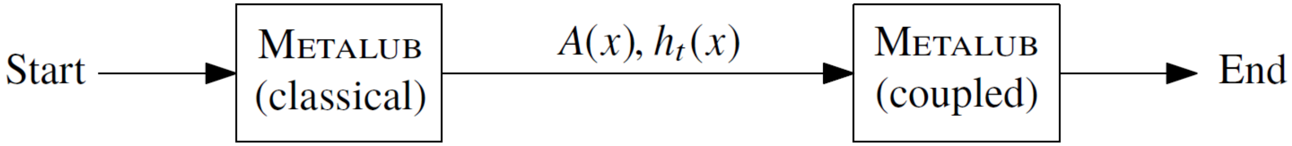
- Mesh-dependence in FE model, when the lubricant pressure becomes equal to the interface pressure
  - Tentative solution: slight reduction of the lubricant pressure







- Insufficient strength/tightness of the coupling
  - Tentative solution: different criterion in adjustment loop of the lubricant flow rate

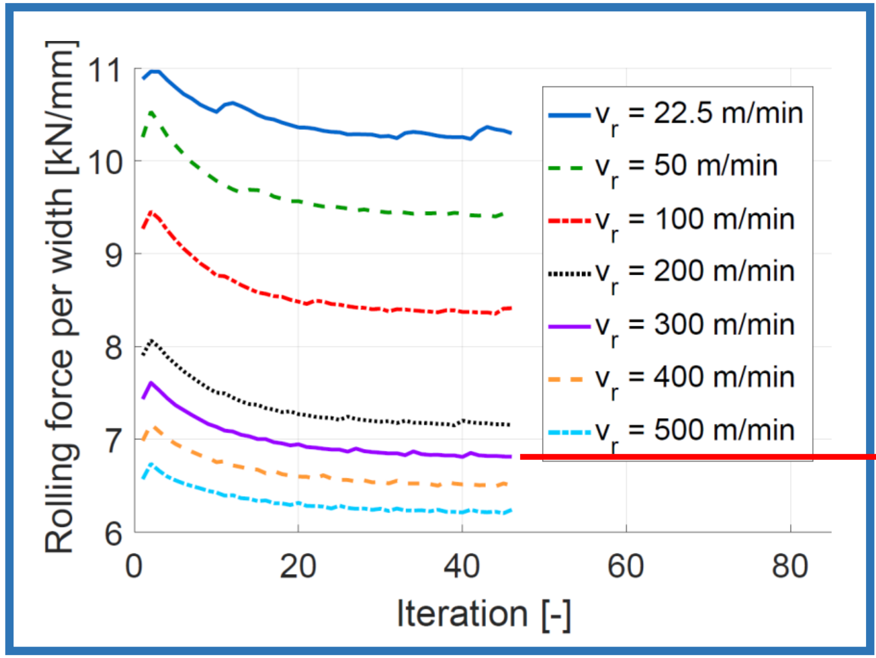


3. Metalub – Metafor coupling

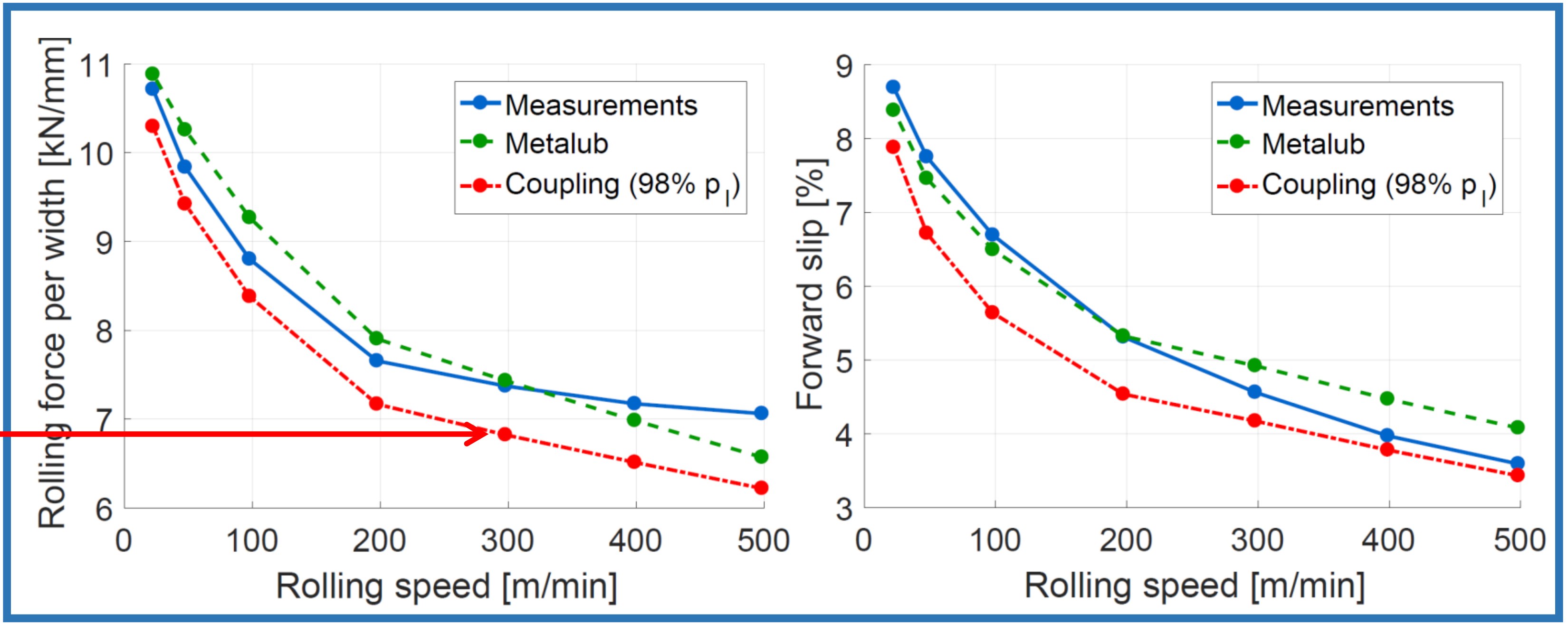
Numerical results (2)

- Procedure converges but this required relatively strong hypotheses
- Wilson & Sheu's law seems to overestimates the relative contact area

Convergence history



Comparison with experimental data and classical Metalub results



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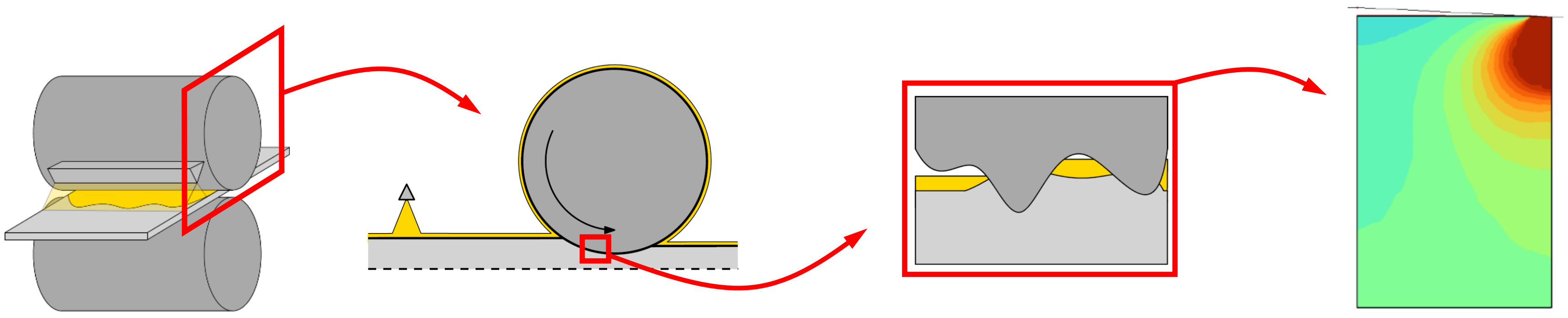
4. Conclusion

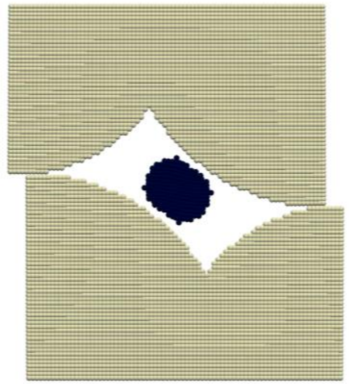
This presentation

- Coupling procedure of Metalub and Metafor
- Analytic asperity flattening equation replaced by FE model: no oversimplified geometry, material, method
- Results: similar to classical Metalub model but Wilson & Sheu seem to overestimate the real contact area
- Limitations: strength of the coupling, identity of lubricant and interface pressure

Future research

- Focus on micro-plasto-hydrodynamic and hydrostatic effects
- Smoothed particle hydrodynamics (SPH)





Animation

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