Numerical Modeling of Friction in Lubricated Cold Rolling

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PhD Thesis Defense

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1. Introduction
2. Experimental data
3. Metalub model
4. Metalub results
5. FE asperity flattening in Metalub
6. SPH asperity flattening
7. Conclusion and outlook
1.1 Rolling in the steel production

Steel slab
Thickness: ~250 mm

Rolling

Car body
~0.8 mm

Tin can
~0.2 mm

Intermediate thickness: 1.5 - 5 mm

Hot rolling at ~1000°C

Cold rolling at ~100°C
1.2 Cold rolling

**Sheet tandem mill**

- **Initial thickness**: 1.5 - 5 mm
- **Final thickness**: 0.3 - 0.8 mm

**Rolling direction**

- **Back-up roll**
- **Mill stand**

**Work roll**

- **Roll bite**: ~20 mm
- **Strip**

**Reduction**: 

\[
\text{Reduction} = r = \frac{t_{in} - t_{out}}{t_{in}}
\]

**Volume conservation**:

\[
v_{out} = \left(\frac{t_{in}}{t_{out}}\right) v_{in} > 1
\]

**Forward slip**:

\[
s_f = \frac{v_{out} - v_r}{v_r}
\]

→ if \( s_f < 0 \), skidding
1.3 Conventional lubrication

- Conventionally, recirculating lubrication systems with an oil-in-water emulsion
  - Passive: constant oil concentration, ...
  - Mixed lubrication

- Relative contact area: $A = A_r/A_a$
- Interface pressure: $p_i = Ap_a + (1 - A)p_l$
- Interface shear stress: $\tau_i = A\tau_a + (1 - A)\tau_l$
  \[ \tau_a \gg \tau_l \]
1.3 Friction and rolling force

- Friction and yield stress $\sigma_Y$ increase the rolling force:

$$\tau_i \rightarrow \sigma_x \rightarrow \sigma_Y = \text{constant} \rightarrow p_i \rightarrow F_r = \int p_i \, dx$$

- Interface shear stress due to friction
- Stress in rolling direction ($< 0$, compression)
- Interface pressure ($> 0$, compression)

$F_r$ by Von Mises yield criterion

$$(\frac{2}{\sqrt{3}}) \sigma_Y = \sigma_x + p_i$$

Diagram illustrating stress and force relationships in rolling direction.
1.4 Industrial problem

- Demand for **harder and thinner sheet products** by car manufacturers
  ➔ lighter cars, lower fuel consumption, less CO2

- This implies a **greater rolling force**.

- Technological constraint: rolling force **limited** by the mill stand

- If **friction was minimized** for a given mill stand, **while preventing skidding**:
  - Harder and thinner products could be rolled;
  - Energy consumption of rolling could be decreased;
  - Roll wear could be reduced;
  - …
1.4 Industrial problem

- Necessity of friction control [Laugier et al., 2014]
  - Computed decrease of rolling force, if effective coefficient of friction is decreased from 0.05 to 0.04 for a reduction of 25% and fixed front and back tensions
  - Strong dependence for hard and thin products

![Graph showing decrease of rolling force vs. entry strip thickness for different grades.](image)

- Friction control required
1.5 Solution: flexible lubrication

• Flexible lubrication (FL) concept
  o **Active**: continuous control of friction
  o By adjusting lubrication conditions depending on rolling conditions

• Application of concept: *control of oil concentration* by additional FL system

[Laugier et al., 2011]
1.5 Solution: flexible lubrication

- **Predictive tool**
  - To determine optimal lubrication conditions (e.g. oil concentration, viscosity, …)
  - Depending on rolling conditions (e.g. rolling speed, product characteristics, …)

- **Extensive research** in the past

- **BUT** no complete tool exists because:
  - Some physical mechanisms cannot be modeled satisfactorily, yet;
  - Individual models of mechanisms could not be combined in one full model, yet.
1.6 Objectives

• General objective:
  Accurately model friction in lubricated cold rolling to minimize friction while preventing skidding by flexible lubrication

• In this thesis:
  1. Determine physical mechanisms to model by most extensive experimental data.
  2. Re-derive, document and extend the Metalub rolling model.
  3. Evaluate predictive capabilities and shortcomings of Metalub by this data.
  4. Introduce MPH lubrication by Finite Element (FE) asperity flattening in Metalub.
  5. Explore Smoothed Particle Hydrodynamics (SPH) to model MPH lubrication.
Outline

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• **Objective:** determine physical mechanisms and validation data

• **Semi-industrial pilot mill** by courtesy of ArcelorMittal (March 2014)

• **Most comprehensive data** available:
  - Roughness measurements
  - Thermo-piezoviscous material laws of the lubricants
  - Hardening laws of strips by plane strain compression tests
  - Large design space:
    - Rolling speeds
    - Rolled products
    - Lubrication conditions
    - Reductions

  ➔ Post-processed: library with 112 rolling scenarios

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2.1 Experimental setup

- **Rolling force**
- **Forward slip**

[Legrand et al., 2015]
2.2 Analysis of experimental data – Influence of rolling speed

- **Hydrodynamic effect** (Test 5B, pure oil)

  \[ v_r \rightarrow h_t \rightarrow A \rightarrow \mu \rightarrow F_r, s_f \]

  - Rolling speed
  - Oil film thickness
  - Relative contact area
  - Friction
  - Rolling force
  - Forward slip

![Graphs showing the relationship between rolling speed and various parameters](image-url)
2.2 Analysis of experimental data – Influence of rolling speed

- **Viscoplasticity** (Test 6, pure oil, different rolled product)

\[
\begin{align*}
 v_r & \uparrow \\
 \rightarrow & D_p \uparrow \\
 \rightarrow & \sigma_Y \uparrow \\
 \rightarrow & F_r \uparrow \\
\end{align*}
\]

- Rolling speed
- Effective plastic strain rate
- Yield stress
- Rolling force

(decrease still due to hydrodynamic effect)
### 2.2 Analysis of experimental data – Influence of lubricant quantity

#### • Starvation (Tests 5B and 4A)

<table>
<thead>
<tr>
<th>Condition</th>
<th>• If less oil is provided to roll bite than it can absorb:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_L \downarrow$</td>
<td>$h_t \downarrow$</td>
</tr>
</tbody>
</table>

- Oil film thickness provided by lub. syst.
- Oil film thickness in roll bite
- Relative contact area
- Friction
- Rolling force
- Forward slip

**Condition:**

- If less oil is provided to roll bite than it can absorb:
  - Less oil provided
  - $h_t$ : maximum film thickness in full-flooded lubrication

- Otherwise, film thickness in roll bite unchanged:
  - Less oil provided
  - $h_t = h_p$ (c)

**FL** = flexible lubrication system
**RE** = recirculating lubrication system
2.2 Analysis of experimental data – Influence of lubricant quantity

- Starvation (Tests 5B, 4A and 5A)
  ➔ Friction control by flexible lubrication

FL = flexible lubrication system; RE = recirculating lubrication system
2.2 Analysis of experimental data – Influence of reduction

- Geometrical effect (Test 8)

\[ r \xrightarrow{} l_{rb} \xrightarrow{} F_r, s_f \xrightarrow{} \]

Reduction  \rightarrow  Length of roll bite  \rightarrow  Rolling force  \rightarrow  Forward slip

Evolution “as expected”
2.2 Analysis of experimental data – Influence of reduction

- Micro-plasto-hydrodynamic/static (MPH) lubrication (Test 7, different rolled product)

\[
\frac{r}{p_l} \rightarrow A \rightarrow \mu \rightarrow \frac{F_r}{s_f}
\]

Reduction \rightarrow Lubricant pressure \rightarrow Relative contact area \rightarrow Friction \rightarrow Rolling force \rightarrow Forward slip

Rolling direction

(a) Roll

(b) Strip

Rolling direction

Lubricant film breaking

Strip indentation

Lubricant pressurization in surface pockets

Lubricant permeation into solid contact zone

Forward slip - \( s_f \)[%]

Reduction - \( r \)[%]
2.3 Intermediate conclusion

- Interacting mechanisms to include in model, mainly:
  - Hydrodynamic effect
  - Starvation
  - Viscous friction
  - Work hardening
  - Viscoplasticity
  - Geometrical effect
  - Asperity flattening
  - MPH lubrication

- Post-processed validation data
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3.1 Objective

- Highly-specialized modeling codes

- Shortcomings:
  - Different versions
  - No consistent documentation
  - Some physical mechanisms not yet modeled

- Objective: re-derive, document and extend (in blue in the following slides) the Metalub model
3.2 System of equations

- Mechanics of the strip
  - Slab method: 1D, neglected internal shear stresses

- Material laws
  - Elastoplasticity
  - Viscoplasticity (new)
  - Thermoplasticity (new)

\[
\sigma_Y(\overline{\varepsilon}^p, \overline{D}^p, T_s) = \left[ A + B (\overline{\varepsilon}^p)^n \right] \left( 1 + \eta_s \ln \frac{\overline{D}^p}{D_0^p} \right) \left[ 1 - \left( \frac{T_s - T_0}{T_m - T_0} \right)^m \right]
\]

[Johnson and Cook, 1983]
3.2 System of equations

- Roll flattening models
  - Rigid: circular or non-circular
  - Adapted radius: Hitchcock (1935), Bland and Ford (1952)
  - Elastic deformation: Jortner et al. (1960); Meindl (2001, new)

- Geometric contact description

\[ h_t = z_r - \frac{t_s}{2} \] (new)

\[ u_r(p_i, \tau_i) \]

\[ u_\theta(p_i, \tau_i) \]
3.2 System of equations

- Asperity flattening models
  - Relation between:
    - Relative contact area $A$
    - Pressure on top of asperities $p_a$
    - Lubricant pressure $p_l$
    - Plastic strain rate of the strip along rolling direction $D_x^p$
  - Analytical models in Metalub:
    - Wilson and Sheu (1988, by upper bound results)
    - Marsault and Sutcliffe (1998, by slip line results)
    - Sutcliffe (1999) based on Korzekwa et al. (1992, by FE results, new)
3.2 System of equations

- Lubricant flow
  - Average Reynolds equation with flow factors (corrected) to include roughness
    \[
    \frac{\partial p_l}{\partial x} = \frac{12\eta}{\phi_x h_t^3} \left( \frac{v_s + v_r}{2} h_t + \frac{v_s - v_r}{2} R_q \phi_s - Q \right)
    \]
  - Lubricant shear stress (shear stress factors, new)
    \[
    \tau_l = \frac{\eta(v_r - v_s)}{h_v} \quad \text{with} \quad h_v = \frac{h_t}{1 - A}
    \]
    \[
    \tau_l = \begin{cases} 
    \frac{\eta(v_r - v_s)}{h} (\phi_f - \phi_{fs}) - \phi_{fp} \frac{h}{2} \frac{\partial p_l}{\partial x}, & \text{if } h > 0 \\
    \frac{\eta(v_r - v_s)}{h_v} - \frac{h_v}{2} \frac{\partial p_l}{\partial x}, & \text{otherwise.}
    \end{cases}
    \]
3.2 System of equations

- Thermal model (new)
  - In the past, coupling with ThermRoll code (Mines ParisTech, Bouache et al., 2009) but abandoned with Stephany’s Metalub version
  - Strip temperature $T_s$: adiabatic heating due to plastic deformation and friction
    \[
    \frac{\partial T_s}{\partial x} = \frac{1}{\rho_s c_s v_s} \left[ \beta_s \left( D_x^p \sigma_x + D_z^p \sigma_z \right) + \frac{\tau_i (v_r - v_s)}{t_s} \right]
    \]
    Taylor-Quinney coefficient $\approx 0.9$
  - Lubricant temperature $T_l$:
    - Isothermal: $T_l = T_l^0$
    - Strip temperature: $T_l = T_s$ or $T_l = \begin{cases} T_l^0 & \text{if } T_s < T_l^0 \\ T_s & \text{otherwise} \end{cases}$
    - Heating due to friction: $\frac{\partial T_l}{\partial x} = \frac{\beta_l}{\rho_l c_l v_s} \frac{\tau_i (v_r - v_s)}{h_t}$ $\beta_l$: percentage of friction energy
3.3 Full Metalub model

- Division of roll bite into zones depending on:
  - Contact status
  - Deformation mode (elastic or elastoplastic)
  - High-speed hypothesis: $p_l = p_i$

- System of equation for each zone

- Zones:
  1. Hydrodynamic inlet
  2. Mixed inlet
  3. Low-speed work
  4. Low-speed outlet
     - Contact?
     - Yielding?
     - Elastic?

- Full Metalub model
  - Roll
  - Strip
  - 1. Hydrodynamic inlet
  - 2. Mixed inlet
  - 3. Low-speed work
  - 4. Low-speed outlet
  - 3’. High-speed work
  - 4’. High-speed outlet
  - Interface pressure $p_i$
  - Lubricant pressure $p_l$, low-speed
  - Lubricant pressure $p_l$, high-speed

- Diagram showing pressure vs. position in rolling direction.
3.3 Full Metalub model

Illustration: short version of system of equations in low-speed work zone (documentation, unification)

\[ z_r = z_r(x) \]
\[ h_1 = z_r - \frac{I_s}{2} \]
\[ h_1 \equiv h_1(x) \]
\[ h = h(h_i) \]
\[ A \equiv A(h) \]
\[ A \equiv A(x) \]

\[ \tau_i = A \tau_a + (1 - A) \tau_f \text{ or } A \tau_a \]
\[ \phi_x = \phi_x(h_1) \text{ or } / \]
\[ \phi_s = \phi_s(h_1) \text{ or } / \]
\[ \frac{\partial p_1}{\partial x} = \frac{12 \eta}{\phi_x h_1^2} \left( \frac{v_x + v_y}{2} h_1 \right) \]
\[ + \frac{v_x - v_y}{R_q \phi_s - Q} \text{ or } 0 \]

Without coupling?

With coupling?

Without lubricant?

With lubricant?

\[ \sigma_y = \sigma_y(T_x^p, D^p, T_s) \]
\[ \tau_y = \sqrt{\frac{\sigma_y}{3}} \]
\[ H_a \equiv p_a - \frac{p_1}{\tau_y} \text{ or } \frac{p_a}{\tau_y} \]
\[ E_p \equiv E_p(A, H_a) \]
\[ p_1 = A p_a + (1 - A) p_1 \text{ or } A p_a \]
\[ \tau_a = \tau_a(v_s, v_r, p_a, \tau_y) \]
\[ T_i = T_i(T_s^p, T_s, T_i) \text{ or } / \]
\[ \eta = \eta(p_1, T_i) \text{ or } / \]
\[ \tau_i = \tau_i(h, h_1, A, \eta, v_s, v_r, \frac{\partial p_1}{\partial x}) \text{ or } 0 \]

\[ \epsilon_x^e = \frac{1}{E_s} \left[ \sigma_x - \nu_s \sigma_y \right] \]
\[ \epsilon_z^e = \frac{1}{E_s} \left[ \sigma_z - \nu_s \sigma_y \right] \]
\[ \epsilon_z^e = \frac{1}{E_s} \left[ \sigma_z - \nu_s \sigma_y \right] \]

\[ \dot{T_i} = \frac{1}{\nu_s} \left( \frac{h_{i,s}}{T_x^p, T_s^p, T_s} \right) \]
\[ \beta_1 = \frac{1}{3} \frac{\sigma_y^2}{G_s} \left( \frac{h_{i,s}}{3G_s} \right) \]

\[ \dot{D}_x^e = \frac{\partial \epsilon_x^e}{\partial x} \]
\[ 0 = D_x^e + D_y^e + D_z^e \]
\[ D_y^e = 0 \]
\[ D_z^e = D_x^e + D_z^e \]
\[ \frac{\partial h}{\partial x} = -\frac{D_y^e T_s}{v_s E_p} \]
\[ D^p = \frac{\sqrt{2}}{3} \left[ (D_x^e - D_x^e T_s) + (D_z^e - D_z^e T_s)^2 \right] \]
\[ s_x = \sigma_x + p \]
\[ s_z = \sigma_z + p \]
\[ s_y = \sigma_y + p \]
\[ \frac{\partial T_i}{\partial x} = \frac{1}{\rho_s c_s} \left[ \beta_s (D_x^e \sigma_x + D_z^e \sigma_z) \right] \]
\[ \frac{\partial T_i}{\partial x} = \frac{1}{\rho_s c_s} \left[ \beta_s (D_x^e \sigma_x + D_z^e \sigma_z) \right] \]

\[ \frac{\partial \epsilon_x^e}{\partial x} \]
\[ \frac{\partial \epsilon_x^e}{\partial x} \]
\[ \frac{\partial \epsilon_x^e}{\partial x} \]

\[ \frac{\partial \epsilon_x^e}{\partial x} \]
3.3 Full Metalub model

- General Metalub algorithm
  - Based on 4 nested adjustment loops
  - Convergence not straightforward
  - Improvements of robustness
    - Removal of unnecessary criteria
    - Initial conditions closer to solution
3.4 Metalub implementation

- Implemented in C++ with Python interface and Graphical User Interface in PyQt
  - Completely refactored (21k lines in 169 core C++ files with ~200 regression tests)
  - Improved robustness and coding style in a spirit of continuity
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4.1 Numerical parameter calibration

- **Objective**: evaluate predictive capabilities and shortcomings of the Metalub model

- First **systematic** calibration of numerical parameters
  - In the past: numerous parameters, calibration by trial and error
  - Now: less parameters, systematic choice
    - **numerical error estimation, reduced computation time, prevention of non-convergence**

Numerical parameters of the adjustment loop, layer by layer

- Integration steps
- Front tension tolerance
- Front tension $\sigma_x(x_{\text{out}})$
- Entry speed $v_{\text{in}}$
- Non-convergence, if tolerances of inner loops not strict enough
4.2 Physical parameter calibration

- **Hydrodynamic effect** (Test 5B, pure oil)
  - Overall improvement of old predictions, especially the forward slip
  - Hypotheses (of new predictions):
    - Adjustment: boundary coefficient of friction, **thermoplasticity coefficient** (instead of yield stress)
    - Constant lubricant temperature at roll bite entry
    - Neglected lubricant shear stress in roll bite

\{ Shortcoming: missing prediction of lubricant temperature \}

[Graphs showing rolling force per width and forward slip vs. rolling speed]
4.2 Physical parameter calibration

- **Starvation** (Test 4A, 2% oil emulsion)
  - Overall improvement of old predictions
  - Hypotheses (of new predictions):
    - The same as previously
    - Manually adjusted lubricant film thickness $h_{t,\text{in}}$ at entry of roll bite
      - Shortcoming: missing prediction of this entry film thickness

\[ Rq = \text{Composite root-mean-square roughness of roll and strip} \]
4.2 Physical parameter calibration

- **Viscoplasticity** (Test 6, pure oil, different rolled product)
  - Significant **improvement** of old predictions obtained by wrong starvation hypothesis
  - Hypotheses (of new predictions):
    - The same as previously (but no starvation)
    - **Adjusted viscoplasticity coefficient** (the same for all rolling speeds)
      - Shortcoming: viscoplasticity coefficient **not identified by experimental testing**
4.2 Physical parameter calibration

- **Influence of thickness reduction** (Test 8)
  - Overall good prediction (no old prediction available)
  - Improvement by decreasing the boundary coefficient of friction $\mu_C$ with reduction
    - Suggests micro-plasto-hydrodynamic/static lubrication

$$\tau_a = \mu C p_a$$

![Graph showing rolling force per width and forward slip versus reduction with different values of $\mu_C$.]
4.2 Physical parameter calibration

- Micro-plasto-hydrodynamic/static (MPH) lubrication (Test 7)
  - More significant influence of this mechanism
    - Shortcoming: missing prediction of MPH lubrication
    - Clear need for modeling MPH lubrication
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5.1 Asperity flattening

- Conventionally, the relative contact area \( A \) is computed by analytical equations, like Wilson and Sheu:

\[
E_p = \frac{1}{0.515 + 0.345 A - 0.860 A^2} \left( \frac{2}{H_a} - \frac{1}{2.571 - A - A \ln (1 - A)} \right)
\]

with \( E_p = \) non-dimensional form of \( D_x^p \)

\( H_a = \) non-dimensional form of \( (p_a - p_l) \)

- Limitations:
  - Simplified geometry: flat indenters
  - Simplified material law: rigid perfectly plastic
  - Approximate method: upper-bound method
  - No MPH lubrication

- Objective: introduce an enhanced FE asperity flattening model with MPH lubrication in Metalub
5.2 Carretta’s coupling procedure

- Carretta (2017): first finite element (FE) model capable of simulating MPH lubrication in strip drawing
  - Strip drawing with lubricant pocket
  - Simulated in in-house FE solver Metafor
  - Lubricant flow by Arbitrary Lagrangian Eulerian (ALE)
    - Uncoupled flow from FE mesh to prevent mesh distortions
    - Artificial lubricant pipes required for lubricant permeation
5.2 Carretta’s coupling procedure

- MPH lubrication in cold rolling
  - Coupling procedure between Metalub and Metafor
  - FE asperity flattening model similar to previous lubricant pocket in strip drawing
    - Lubricant pipes introduced by shifted contact tool to allow permeation
    - Pressure increase in valleys “opens” pipes and decreases contact → MPH lubrication
  - Converged only, if lubricant pressure not updated based on FE results
    → No real convergence, since influence of FE model on lubricant pressure not considered
5.3 New coupling procedure

- **Simplified model** for gradual improvement towards MPH lubrication

- **New FE asperity flattening model**
  - Roll modeled by fixed rigid contact tool
  - Strip modeled by FE method
  - Interface pressure $p_i$ pushes strip against roll
  - Strip cannot deform laterally

  - **Generalized plane strain state**
    - Strip elongation $l_{x,s}$ due to rolling
  - Lubricant pressure $p_l$ of Metalub applied where no contact exists between roll and strip

![Diagram showing roll, fixed contact tool, strip, and applied pressures](image-url)
5.3 New coupling procedure

- Full coupling procedure
5.3 New coupling procedure

- Numerical results: first Metafor iteration (Test 5B-4)
5.3 New coupling procedure

- **Shortcomings**
  - **Mesh dependence** in FE model, if lubricant pressure \( p_l \) becomes equal to interface pressure \( p_i \)
    - Tentative solution: slight reduction of the lubricant pressure

![Diagram showing mesh dependence and no mesh dependence](image)

Mesh dependence, if \( p_l = p_i \)

No mesh dependence, if \( p_l = 0.95 \cdot p_l \)
5.3 New coupling procedure

- Shortcomings
  - Insufficient strength/tightness of the coupling procedure
    - Results of coupled Metalub computation based on results of classical Metalub computation (instead FE flattening model) different from results of classical Metalub computation.
    - Results should, however, be equal since flattening model unchanged.
    - Tentative solution: different criterion in the adjustment loop of the lubricant flow rate.
5.3 New coupling procedure

- Numerical results: full coupling procedure (Test 5B-4)
  - “Convergence” reached
  - Wilson and Sheu’s equation seems to overestimate the relative contact area, which increases friction and thus, the rolling force

- Intermediate conclusion
  - Convergence but strong hypotheses required
  - Possible computation-intensive solution but still no MPH lubrication
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6.1 Motivation

- **Most promising model of MPH lubrication**: Carretta’s FE model of plane strip drawing

- **Limitations**:
  - Artificial ALE lubricant pipes to allow permeation
  - Large deformations limited by mesh-distortions
  - Long computation time (10 days)
  - 2D model (3D extension not straightforward)

- **Objective**: explore “Smoothed Particle Hydrodynamics” (SPH) method to model MPH lubrication
6.2 Smoothed particle hydrodynamics

- Eulerian, Lagrangian or Arbitrary Lagrangian Eulerian (ALE) meshes in FE method

\[ t = t_0 \quad \text{or} \quad t > t_0 \]

Eulerian:
- ✓ No mesh distortions
- ✗ Difficult boundary tracking

Lagrangian:
- ✗ Mesh distortions
- ✓ Automatic boundary tracking

ALE:
- ✓ No mesh distortions
- ✓ Automatic boundary tracking
- ✗ Mesh motion to be anticipated

- Classical mesh-based versus Lagrangian meshless particle method

Classical mesh-based:
- ✗ Difficult boundary tracking or
- ✗ Mesh distortions or
- ✗ Mesh motion to be anticipated

Lagrangian meshless particle:
- ✓ Automatic boundary tracking
- ✓ No mesh distortions
- ✓ No mesh motion to be anticipated

- SPH: Lagrangian meshless particle method
6.2 Smoothed particle hydrodynamics

- Fundamental concepts
  - Kernel approximation
    \[ f(x) = \int f(x') \delta(x - x') \, dx' \quad \Rightarrow \quad f(x) = \int f(x') W(x - x', h) \, dx' \]
  - Particle approximation
    \[ f(x) = \int f(x') W(x - x', h) \, dx' \quad \Rightarrow \quad f(x_a) = \sum_{b \in S_a} V_b f(x_b) W(x_{ab}) \]
    \[ \nabla f(x_a) = \sum_{b \in S_a} V_b f(x_b) \nabla W(x_{ab}) \]
  - Gradient correction (consistency)
    - Zeroth-order completeness:
      \[ \left[ \nabla f(x_a) \right]^T = \sum_{b \in S_a} V_b \left[ f(x_b) - f(x_a) \right] \otimes \nabla W(x_{ab}) \]
    - First-order completeness:
      \[ \left[ \nabla f(x_a) \right]^T = \sum_{b \in S_a} V_b \left[ f(x_b) - f(x_a) \right] \otimes K_a^{-1} \nabla W(x_{ab}) \]
      with \[ K_a = \sum_{b \in S_a} V_b \nabla W(x_{ab}) \otimes (x_b - x_a) \]
6.2 Smoothed particle hydrodynamics

- **Eulerian SPH for fluids**
  - Variational approach by Bonet and Lok
  - Non-linear compressibility
  - Newtonian viscosity
  - Artificial Monaghan viscosity (stability)

\[
\frac{dv_a}{dt} = \sum_{b \in S_a} \left[ V_a V_b \left( \sigma_a K_a^{-1} + \sigma_b K_b^{-1} \right) + m_a m_b \Pi_{ab} \right] \nabla W(x_{ab}) + m_a b_a + \sum_{b \in S_a} f_{c \ab}^c
\]

- **Total Lagrangian SPH for solids**
  - Tensile instability: total Lagrangian
  - Elasto-J2-plasticity with hardening (P = Piola)
  - Zero-energy mode suppression (HG = HourGlass)

\[
\frac{dv_a}{dt} = \sum_{b \in S_a^0} \left[ V_a^0 V_b^0 \left( P_a K_{0,a}^{-1} + P_b K_{0,b}^{-1} \right) \nabla W(X_{ab}) + f_{\text{HG}}^{ab} \right] + m_a b_a + \sum_{b \in S_a} f_{c \ab}^c
\]

- **Contact interaction**
  - Penalty force

\[
f_{c \ab}^c = -\frac{4}{3} E^* \sqrt{R^*} \delta^{3/2} \frac{x_{ab}}{x_{ab}}
\]
6.2 Smoothed particle hydrodynamics

• Numerical solution method
  o LAMMPS (Plimpton, 1995)
    ▪ Molecular dynamics solver
    ▪ USER-SMD (Ganzenmüller, 2015):
      • Package with this specific SPH formulation
      ▪ Modifications: kernel, post-processing features
  o Computational efficiency
    ▪ Neighbor search: link-cell binning and neighbor lists
    ▪ Domain decomposition with dynamic load balancing
  o Time integration
    ▪ Velocity-Verlet (explicit)
    ▪ Time step stability limit
6.3 Validation tests

- First fluid and fluid-structure interaction (FSI) validation tests of the USER-SMD package
- Tests based on Cerquaglia’s thesis (2019) about PFEM-FEM coupling in MN2L research group
- Water sloshing in an oscillating reservoir [Souto-Iglesias et al.]

Yellow = real water; red = prediction
(20,000 water particles, 2 h CPU, 3 physical cores)
6.3 Validation tests

- Dam break against an elastic obstacle

\[ L = 146 \text{ mm} \]
\[ w = 12 \text{ mm} \]
\[ E = 1 \text{ MPa} \]

(10,440 water particles, 278 solid particles, 10 min CPU, 3 physical cores)
6.3 Validation tests

- Gravity-driven viscous flow
  - Periodic boundary condition along vertical direction: particles reinjected at the top
  - No-slip boundary condition: fixed boundary particles included in particle sum of fluid particles
6.4 Asperity flattening

- **Problem statement [Shvarts and Yastrebov, 2018]:**
  - Lubricated asperity flattening
  - Elastic-perfectly plastic steel
    - Young modulus: 200 GPa
    - Poisson's ratio: 0.28
    - Yield stress: 250 MPa
  - Non-linearly compressible oil
    - Bulk modulus: $2000 + 9.25 \rho_i$ [MPa]
  - Relative contact area as a function of pressure

- **Progressive resolution**
  1. Compression of an elastoplastic solid
  2. Dry asperity flattening
  3. Compression of a fluid
  4. Lubricated asperity flattening
6.4.1 Dry asperity flattening

- Boundary conditions
  - No horizontal displacement of vertical edges
  - Imposed upward speed

- Discretization
  - Coarser boundary than by Lagrangian meshes
  - Asperity amplitude increased
  - ~36,000 particles; 4.5 h CPU time (12 cores)
    - Local refinement required

- Relative contact area computation

- Successful validation
  - By previous FE model of asperity flattening
  - Without mesh distortions in SPH
6.4.2 Lubricated asperity flattening

- Previous configuration with oil
- Almost identical solutions when oil is not compressed
- Increase of relative contact area slowed down by oil in SPH
- Infiltration after ~2000 MPa due to penalty contact
  - Possible solution: boundary condition by Adami et al.
- Artificial permeation at very high pressure (~5000 MPa)
- MPH lubrication? Not yet.
  - Solve shortcomings: boundary conditions, CPU time
1. Introduction
2. Experimental data
3. Metalub model
4. Metalub results
5. FE asperity flattening in Metalub
6. SPH asperity flattening
7. Conclusion and outlook
Conclusion – Original contributions

- **Experimental data**
  - Post-processing and analysis of the most comprehensive data of lubricant cold rolling

- **Metalub model**
  - Re-derivation, documentation, extension and refactoring of the model and its implementation
  - One of the most powerful models of lubricated cold rolling!

- **Metalub results**
  - Evaluation of Metalub’s predictive capabilities and shortcomings based on the previous data

- **FE asperity flattening in Metalub**
  - First coupling procedures between Metalub and the FE solver Metafor with lubricated asperity flattening including the strip elongation

- **SPH asperity flattening**
  - First simulation of complex FSI validation tests by LAMMPS USER-SMD
  - First SPH models of dry and lubricated asperity flattening
Outlook

• Incorporation of a full thermal model into Metalub
  o Similar to ThermRoll and within the Metalub software project

• Incorporation of an analytical MPH lubrication model into Metalub
  o Reduction of relative contact area based on variables that favor MPH lubrication according to Ahmed and Sutcliffe (2001)

• Incorporation of a lubricant film formation model into Metalub
  o Computation of lubricant film thickness at the entry based on Cassarini (2007)

• Extension of experimental data
  o Reduction of modeling uncertainties (viscoplasticity, …)

• Improvement of lubricated asperity flattening by SPH
  o Local refinement of discretization by Spreng (2017); boundary condition by Adami et al. (2012)
Thank you for your attention!
Selected references


Selected references


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