Numerical Simulation of the Friction Stir Welding Process using Lagrangian, Eulerian & ALE Approaches

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Overview

- **Background**
  - The Friction Stir Welding Process
  - Modeling of FSW

- **Numerical models**: FORGE3® & THERCAST®

- **Modeling and experimental results**
  - Plunging phase: comparison between experimental and numerical result
  - Welding phase:
    - Lagrangian / Eulerian simulations capabilities
  - ALE formulation and first results

- **Future work**
Background
Friction Stir Welding Process

- Patented in 1991 by TWI
- A solid-state joining process
- Potential commercial and military users
  - aerospace
  - automotive
  - marine
- Capable of joining aluminum, steel, stainless steel
Different main phases of FSWP

I. Background
1. The process
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FORGE3® & THERCAST®

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1. Plunging phase
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2. Welding phase
   - Eulerian Simulation
   - Lagrangian Simulation
3. ALE formulation
   - Different descriptions
   - The two main steps
   - Dwelling phase

Future Work
Modeling of FSW

Motivation:

- Predict material flow: try to minimize heat input, and eliminate defects
- Use to develop better tooling designs
- Predict mechanical properties of weld: flow & thermal history
- => mechanical properties and eventually microstructure
Approaches in literature

- **CFD approach:** obtain information on material flow, but neglect free surface deformation and effect of deformation history.

- **Lagrangian FE:**
  - use analytical heat source and apply a compressive stress along the weld line; calculate residual stresses
  - simulate material flow, including heat from friction and material deformation; requires complex remeshing

- **Arbitrary Lagrangian Eulerian (ALE) FE:** can simulate flow and include heat from friction and deformation; avoids degeneration of mesh; allows for deformation of free surface
Numerical Models
• Hot, warm, and cold forging (FORGE3®)
  Filling and cooling of foundry parts (THERCAST®)
• 3D thermo-mécanical computation
• Lagrangian (FORGE3®) and /or ALE
  (THERCAST®) Finite Element Formulation
• Automatic Remeshing

Strong form of the mechanical problem:

Pure viscoplastic behaviour (firstly) with thermal coupling

\[ \dot{\varepsilon} = \dot{\varepsilon}_{\text{vp}} + \dot{\varepsilon}_{\text{th}} \]

\[ s = \sigma + p \mathbf{I} = 2K_{(T,\varepsilon)} \left( \sqrt{3\dot{\varepsilon}} \right) m_{(T,\varepsilon)}^{-1} \dot{\varepsilon}_{\text{vp}} \]

\[ \dot{\varepsilon}_{\text{th}} = \alpha \dot{T} \mathbf{I} \]

Incompressibility and equilibrium

\[ \text{tr}(\dot{\varepsilon}_{\text{vp}}) = \text{div} \mathbf{v} - 3\alpha \dot{T} = 0 \]

\[ \nabla \cdot \sigma + \rho g - \rho g = \nabla \cdot s - \nabla p + \rho g - \rho \gamma = 0 \]
Heat Equation

\[
\rho c \frac{dT}{dt} - \text{div}(k \nabla T) = \dot{W} \quad \text{dans } \Omega ; \quad \text{avec } \dot{W} = \sigma : \dot{\varepsilon} \quad + \text{ B.C.}
\]

» Heat transfer by convection/radiation:

\[-k \nabla T \cdot n = h_{cr} \left( T + T_{ext} \right)\]

» Conduction with tools and heat due to friction:

\[-k \nabla T \cdot n = -h_{cd} \left( T + T_{tool} \right) + \frac{b}{b + b_{tool}} \tau . v_g\]

**Heat Sources**
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Future Work

- Time discretisation
  \[ X^{t+\Delta t} = X^t + V^t \Delta t \]

- Newton-Raphson algorithm

- Preconditioned Conjugate Gradient solver

- Parallel resolution by mesh partitioning

- Updated Lagrangian formulation
  with automatic remeshing (topological, MTC)

• Finite Element discretisation & FORGE3® solveur

\[ \frac{\partial}{\partial t} \mathbf{v} + \mathbf{v} \cdot \nabla \mathbf{v} - \nu \nabla^2 \mathbf{v} = \mathbf{f} \]

\[ \nabla \cdot \mathbf{v} = 0 \]
Modeling and experimental results
Plunging phase

Plunge experiment

- Thermocouples
  - Weld Material—12.7 mm to 20.6 mm radius, at a depth of 1.6 mm
  - FSW Tool—1.2 mm of depth
FORGE3® simulation

- 6 Second Plunge
  1.19 mm/s plunge speed, 600 RPM
- Lagrangian sensors were placed in the FSW weld material (1.6 mm)
- Remesh every 4 time steps
- Adiabatic contact heat transfer condition, Convective cooling on free surfaces
Comparison: experimental / numerical results

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Future Work
Workpiece Temperature Rise

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Future Work
A Comparison of the Experimental and Forge3 Temperatures at 12.7 mm (6.35 mm Pin Length)

- **Workpiece Temperature Rise**

- **Weld Material Temperature Profiles**
• Tool Temperature and Workpiece Isotherms

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Future Work
Welding phase

Geometric data:
- part: 127mm x 127mm x 19mm
- experimental welding tool (concave shoulder, 3° tilted):
  - pin: Ø=8mm, h=7mm
  - shoulder: Ø=25.4mm, h=90mm
    (cooling → 10°C forced on 60mm from the top surface)
  - rotational speed: 15 rotation/second
  - advance speed: 5 mm/second

Thermal and mechanical data:
- Convective exchange with air on all surfaces (h<sub>cr</sub>=30 W/m²)
- Same standard behavior law for aluminum
- Norton viscoplastic law: coefficient α from 0.6 at 0°C to 1.1 at 650°C (linear evolution)
  q from 1 at 0°C to 0.5 at 650°C (linear evolution)
- Density, conductivity, and heat capacity in paper
Pure Eulerian Simulation : neglect of free surfaces movement / no remeshing

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Future Work

6s simulation with an arbitrary initial temperature
- 6s simulation with an arbitrary initial temperature field

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Future Work

Plunge experiment
 FORGE3® simulation
 Comparison

Eulerian Simulation
 Lagrangian Simulation

Different descriptions
 The two main steps
 Dwelling phase

The two main steps

Time = 0.000 (1 of 14)
Lagrangian capabilities: simulation of a defect during “cold welding”

Geometric data:
- part: 60mm x 60mm x 20mm
- simplified welding tool (no concave shoulder, 3° tilted):
  - pin: Ø=6mm, h=6mm
  - shoulder: Ø=20mm, h=60mm
  - rotational speed: 15 rotation/second
  - advance speed: 1 mm/second

Thermal and mechanical data:
- Adiabatic rigid tool ➔ heat due to friction and plastic deformation only
- Standard behavior law for aluminum in hot forming process (Hansel Spitel law):
  \[
  \sigma_f = A e^{-0.0479T} \left( \frac{0.01383 \dot{\varepsilon}}{\dot{\varepsilon}} \right)^0.09964 \frac{0.0011}{\dot{\varepsilon}}
  \]
- “Strong” friction (Coulomb law):
  \[
  \tau = 0.3 \sigma_n \left\| \frac{\Delta V}{\Delta n} \right\| \quad \text{if} \quad 0.3 \sigma_n < K_{(T,\varepsilon)}
  \]
  \[
  \tau = 0.6 K_{(T,\varepsilon)} \left\| \frac{\Delta V}{\Delta n} \right\| \quad \text{if} \quad 0.3 \sigma_n > 0.6 K_{(T,\varepsilon)}
  \]
- 6s simulation with a low initial temperature

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Future Work
ALE formulation

Different Descriptions:

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Future Work

- Lagrangian mesh
- Eulerian mesh
- ALE mesh
The two main steps of the ALE description implemented in Thercast:

- Convective terms treatment

\[
\begin{aligned}
\frac{d\varphi}{dt} &= \frac{d_g\varphi}{dt} + \mathbf{c} \cdot \nabla \varphi \\
\mathbf{c} &= \mathbf{v} - \mathbf{w}
\end{aligned}
\]

v: material velocity  
w: mesh velocity

Splitting Method (used firstly)
= lagrangian iteration + transport on the new mesh

Convective Approach (upwind aspect)
\[
\varphi_{\text{ALE}}^{t+\Delta t} = \varphi_{\text{ref}}^t + \int_{\Delta t} \frac{d_g\varphi}{dt}
\]

→ Mesh velocity computation: w

Future Work
**ALE simulation of the dwelling phase**

### Geometric data:
- **part**: 127mm x 127mm x 19mm
- **simplified tool** (no concave shoulder, not tilted):
  - **pin**: Ø=8mm, h=7mm
  - **shoulder**: Ø=25.4mm, h=90mm
    (cooling ➔ 10°C forced on 60mm from the top surface)
  - rotational speed: 15 rotation/second
  - no advance speed

### Thermal and mechanical data:
- Exchange with bottom plate model by a coefficient $h_{cr} = 300 \text{ W/m}^2$ and exchange with air on other surfaces ($h_{cr} = 30 \text{ W/m}^2$)
- Same standard behavior law for aluminum
- Norton viscoplastic law
- Density, conductivity, and heat capacity depend on temperature
• 15s simulation without any remeshing
  ➔ stability of ALE formulation
  (Initial temperature obtained after plunging phase)

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Future Work
Comparison with experimental results

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<th>Norton Friction</th>
<th>T (°C)</th>
<th>α</th>
<th>q</th>
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Future Work
Summary

• Lagrangian, Eulerian, and ALE approaches have been used to simulate FSW, using Forge3® and Thercast®

• The ALE approach is best adapted for modeling this process, because it takes into account changes in the free surface while avoiding element degeneration in high deformation zones

Future Work

• Implementation of a complete ALE formulation in Forge3® code

• Test of different transport techniques: - nodal upwind
  - SUPG
  - MLS / RBF
  with use of adaptive remeshing to minimize transport diffusion

• Further comparison between experiment and simulation

• Experimental work to study friction, material behavior, and heat transfer coefficients