Santos Vilaca da Silva, Pedro


Published: 01/01/2014

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Fundaments of the Modelling of FSW

Pedro Vilaça
pedro.vilaca@aalto.fi

November, 2014
HGZ, Hamburg, Germany
Modelling of Friction Stir Welding

Why Modelling?

To Know the Physics of FSW

To Control the FSW Process

To Predict

- Tool life
- Defects
- Performance Properties (e.g., Mechanical, Creep, Corrosion)
- Residual Stress and Deformation

Validated Model

To Develop

- Tool Material
- Tool Geometrical Features
- Clamping System
- Process Parameters

To Assess

- Temperature + Hydrostatic Pressure @ 3D viscoplastic material flow (near field)
- Temperature + Stress/Strain distribution @ elasto-plastic domain (far field)
- Metallurgical history
Friction Stir Welding Process
Fundaments – 3D Material Flow

Perspective of visco-plastic material flow in longitudinal (x-z) plan... Taken from the Retreating/Flow side

FSW is ALIVE inside!
Modelling of Friction Stir Welding
Complex Multiphysics Coupled Phenomena

Movement of the tool

Interfacial Friction (material / tool)

Materials plastic flow and deformation

Heat dissipation by internal friction (viscous)

Heat Generation

Superficial appearance
Defective joints
Mechanical properties of the different regions

Metallurgical structure changes (dynamic recrystallization of the Nuget)
Friction Stir Welding Process
Fundaments – Hot versus Cold Material Flow Pattern

Vickers Hardness Field

FSW Classification

- Hot: $\Omega$ (rpm), $v$ (mm/min)
  - HAZ
  - TMAZ

- Cold: $v$ (mm/min), $\Omega$ (rpm)
  - HAZ
  - TMAZ

(Sample: AA6065-T4; $t=3.9$ mm)

Courtesy of HZG
Fundamentals of Modelling

Modelling Structure

\[ \rho C_v \left( \frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right) = \]

Internal Energy Balance

\[ k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \]

\[ \frac{\partial k}{\partial T} \left( \frac{\partial T}{\partial x} \right)^2 + \left( \frac{\partial T}{\partial y} \right)^2 + \left( \frac{\partial T}{\partial z} \right)^2 \right) + A \]

Energy Flow In - Energy Flow Out

Formulation

Discretization

Solution

Physical Model

Mathematical Model

Discrete Model

Discrete Solution

Solution Error

Discretization Error + Solution Error

Formulation Error + Discretization Error + Solution Error

Verification and Validation
Fundamentals of Modelling
Formulation Methods

Lagrangian Description

ALE Description

Eulerian Description

Nodes
Material Points
Nodal Trajectory
Material Point Trajectory
Fundaments of Modelling
Discretization Methods

Discretization

Mathematical Model → Discrete Model

- Finite Element Method
- Finite Difference Method
- Finite Volume Method
- Meshless Method (SPH)
# Fundamentals of Modelling

## Integration Methods

<table>
<thead>
<tr>
<th>Implicit</th>
<th>Explicit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ddot{u} = M^{-1}(P - I)$</td>
<td>System of nonlinear equilibrium equations</td>
</tr>
<tr>
<td>$\ddot{u}_{t+\Delta t} = \ddot{u}_t + \Delta t((1-\gamma)\dddot{u}<em>t + \gamma\dddot{u}</em>{t+\Delta t})$</td>
<td>$\dot{u}_{t+\Delta t} = \dot{u}_t + \Delta t\ddot{u}_t + \frac{\Delta t^2}{2}(1-\beta)\dddot{u}<em>t + \beta\dddot{u}</em>{t+\Delta t}$</td>
</tr>
<tr>
<td>$\beta = \frac{1}{4}(1-\alpha)^2$ ; $\frac{1}{3} \leq \alpha \leq 0$ ; $\gamma = \frac{1}{2}$</td>
<td>$\dot{u}_{t+\Delta t} = \dot{u}_t + \frac{\Delta t}{2}(\ddot{u}<em>t + \ddot{u}</em>{t+\Delta t})$</td>
</tr>
<tr>
<td>Residual $\rightarrow 0 \Rightarrow$ iteration convergence</td>
<td>Stable time increment</td>
</tr>
<tr>
<td>$R_{t+\Delta t} = M\dddot{u}<em>{t+\Delta t} + (1+\alpha)\left(I</em>{t+\Delta t} - P_{t+\Delta t}\right) - \frac{1}{2}\alpha\left(I_t - P_t + I_r - P_r\right) + L_{t+\Delta t}$</td>
<td>$\Delta t_{stable} = \frac{L}{C_d}$</td>
</tr>
<tr>
<td>$M$ – mass matrix</td>
<td>$P$ – external force vector</td>
</tr>
<tr>
<td>$u$ – displacement vector</td>
<td>$\dot{u}$ – velocity vector</td>
</tr>
<tr>
<td>$I$ – internal force vector</td>
<td>$\ddot{u}$ – acceleration vector</td>
</tr>
</tbody>
</table>

[Image of the table and diagram]
Example of Numerical Modelling Approach

Integration CSM / CFD

- Elastic - Plastic
  Analysis of the plates remote from tool HAZ and Base Material

- Viscous - Plastic
  Analysis near the tool Nugget and TMAZ

Structural Mechanics Approach
  (E.g. Abaqus)

Fluid Dynamics Approach
  (E.g. Fluent)

Results
  Residual Stress Field
  Residual Deformation
  Thermal History of the HAZ

Results
  Material Flow for different tool geometries
  Thermal History at the vicinity of the tool

Integration

FE Mesh
- Pressure
- Temperature

Updated at interface:
- Temperature
- Pressure
Example of Numerical Modelling Approach

Description of the Integration CSM / CFD

This integration imposes a thermal field in the CSM domain equal to the CFD thermal field in the vicinity of the tool: $D > \varnothing$Shoulder

The integration generates an history that moves the thermal field across the CSM domain to simulate the welding process...
Example of Numerical Modelling Approach

Features of the Integration CSM / CFD

<table>
<thead>
<tr>
<th>Computational Solids Mechanics (CSM)</th>
<th>Computational Fluid Dynamics (CFD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite Element Method</td>
<td>Finite Volume Method</td>
</tr>
</tbody>
</table>

- Implicit Integration Scheme
- Thermo-Mechanically Coupled Analysis

<table>
<thead>
<tr>
<th>Transient Regime</th>
<th>Steady-State Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lagrangean Analysis</td>
<td>Eulerian Analysis</td>
</tr>
</tbody>
</table>

- Elastic-Plastic Temperature Dependent Material Model
- Viscous-Plastic Material Model (Zener-Hollomon)
- Stick Friction Contact Model
Visco-plastic Material Modelling for CFD
Zener-Hollomon Model

The application of a fluid mechanics based model requires a viscosity function to simulate the temperature dependent non-Newtonian material flow behavior.

Using the Perzina’s visco-plastic model:

\[ \dot{\varepsilon}_{ij} = \frac{1}{2\eta} S_{ij} \]
\[ S_{ij} = \sigma_{ij} - \delta_{ij}\rho \]
\[ \rho = \frac{\sigma_{ii}}{3} \]

where:

\[ \dot{\varepsilon}_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]

With the viscosity for an ideal visco-plastic flow:

\[ \eta(T, \ddot{\varepsilon}) = \frac{S(T, \ddot{\varepsilon})}{3 \ddot{\varepsilon}} \]

where:

\[ \ddot{\varepsilon} = \sqrt{\frac{2}{3} \ddot{\varepsilon}_{ij} \ddot{\varepsilon}_{ij}} \text{ - Effective strain rate} \]
\[ S(T, \ddot{\varepsilon}) \text{ - Effective deviatoric flow stress} \]
Material Modelling for CFD
Zener-Hollomon Model

The Zener-Hollomon parameter describes the influence caused by deformation temperature and effective strain rate.

\[ S(T, \dot{\varepsilon}) = f[Z(T, \dot{\varepsilon})] = f[\dot{\varepsilon} \exp\left(\frac{Q}{RT}\right)] \]

where:  
T – Absolute temperature [K]  
Q – Activating heat energy [J/mol]  
R – Universal gas constant [J/(mol.K)]

Sellars and Tegart (1971) and Shepard and Wright (1979) proposed the following form of the viscosity for metals:

\[ \eta(T, \dot{\varepsilon}) = \frac{1}{3 \dot{\varepsilon} \alpha} \ln \left\{ \left(\frac{Z(T, \dot{\varepsilon})}{A}\right)^{\frac{1}{n}} + \left[\left(\frac{Z(T, \dot{\varepsilon})}{A}\right)^{\frac{2}{n}} + 1\right]^{\frac{1}{2}} \right\} \]

where:  - A, \alpha, n are fitting constants
Material Modelling for CSM
Elastic-Plastic Material with Thermal Expansion

Solid Mechanics
Thermo-Mechanical Analysis:

\[
\varepsilon^{\text{thermal}} = \alpha_{\text{expansion}} \Delta T \Rightarrow \sigma = E \left( \varepsilon - \varepsilon^{\text{thermal}} \right)
\]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E=73 GPa ; v=0.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Temperature (°C) vs. Co-efficient of expansivity

- Cooling 1110 - 725 (Austenite)
- Phase Transformation 725 - 535
- Cooling to Ambient 535- 20 (Martensite/Bainite)

Thermal Properties Depending on Temperature

K (T) [W/m.K] | Cp (T) [J/Kg.K]

| Fusion Temperature [K] | ? |
| Solidus Temperature [K] | ? |
| Liquidus Temperature [K] | ? |

Change in length per unit length (\(dl/l\))

- Co-efficient of expansivity 14.94 x 10\(^{-6}\) (°C)
- Co-efficient of expansivity 22.78 x 10\(^{-6}\) (°C)
- Co-efficient of expansivity -0.73 x 10\(^{-6}\) (°C)
Modelling of Friction Stir Welding

Final Remarks

- Highly non-linear character (geometric, material, formulation)
- Physical properties vary throughout the FSW process \(\iff\) Demands: Reliable Material Model Data (depending on: Temperature + Strain Rate)
- Heat generated at sliding interfaces between the tool and the workpieces material depends on a frictional complex phenomena
- Visco-plastic flow dissipates significant heat to workpieces thus the correct simulation of material flow in the TMAZ is fundamental
- Thermal flow into the tool, anvil and clamping system does affect significantly the thermal field in the workpieces
- FSW model needs to allow hybrid formulation (solid and fluid mechanics)
- Not possible to apply symmetry simplifications
- Complex tool profile implicates a complex discretization
Thank You

Pedro Vilaça
pedro.vilaca@aalto.fi

November, 2014
HGZ, Hamburg, Germany