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Materials Engineering

Materials Joining and NDT

Fundaments of the Modelling of FSW

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High Integrity Low Distortion Assembly

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HGZ, Hamburg, Germany

Modelling of Friction Stir Welding

Why Modelling ?

To Know **the Physics of FSW**

To Control **the FSW Process**

Validated Model

To Predict

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

To Develop

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

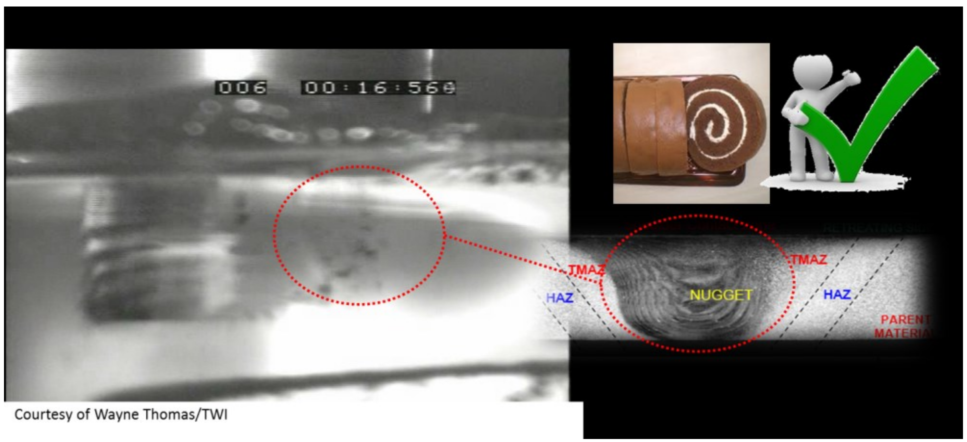
To Assess

- ☞ **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



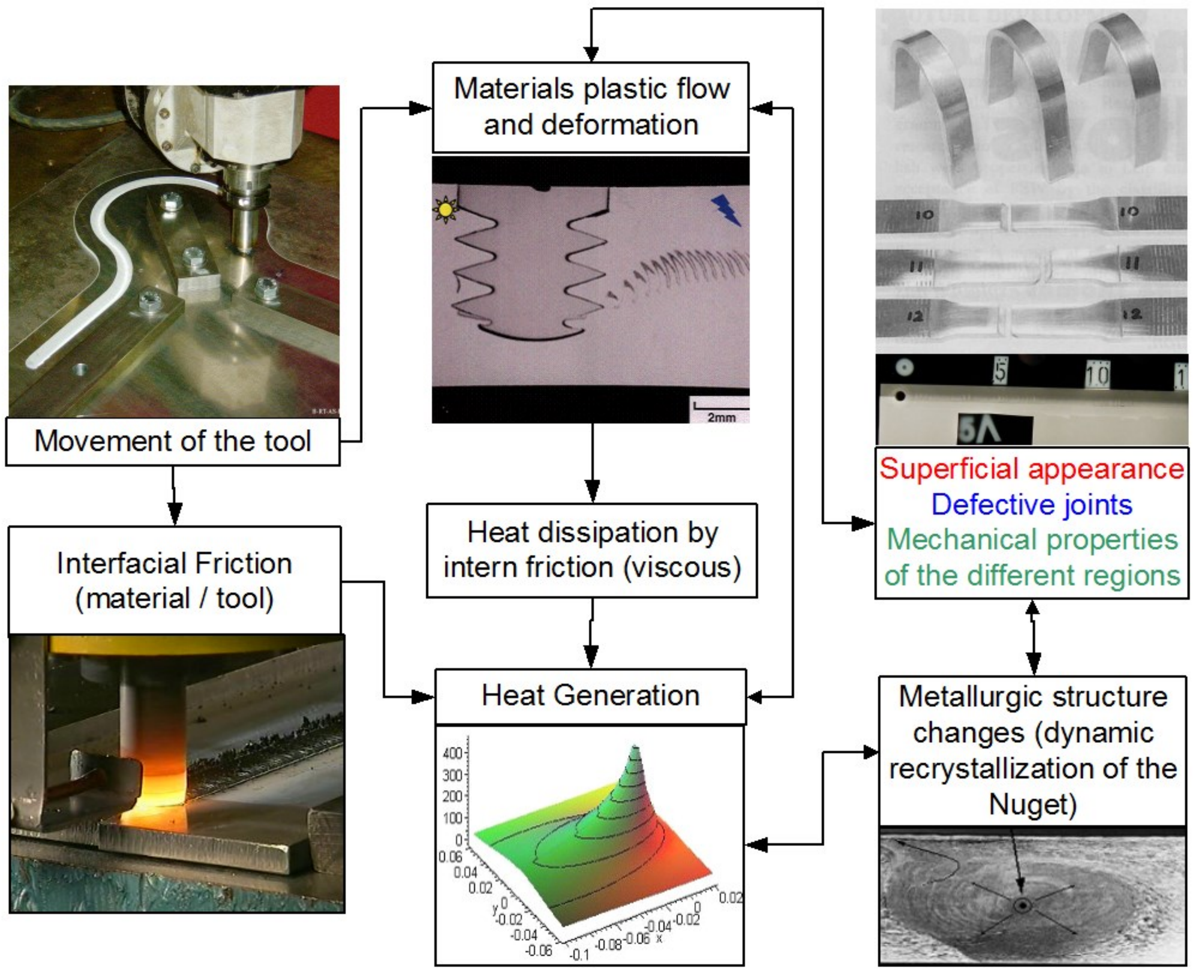
Courtesy of Wayne Thomas/TWI

Courtesy of Wayne Thomas/TWI

FSW is ALIVE inside!

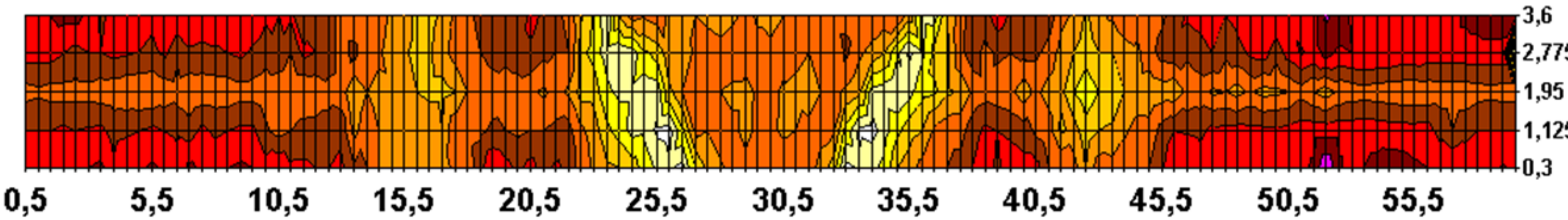
Modelling of Friction Stir Welding

Complex Multiphysics Coupled Phenomena



Friction Stir Welding Process

Fundaments – Hot *versus* Cold Material Flow Pattern



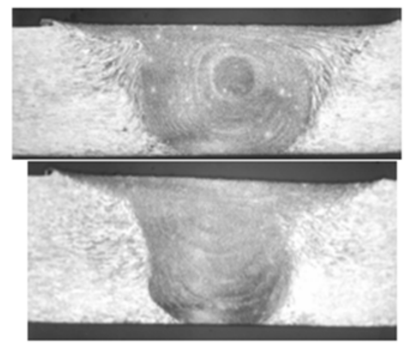
Vickers Hardness Field

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

$$\frac{\Omega\,[\mathrm{rpm}]}{v\,[\mathrm{mm/min}]} = \frac{2000}{500} = 4$$

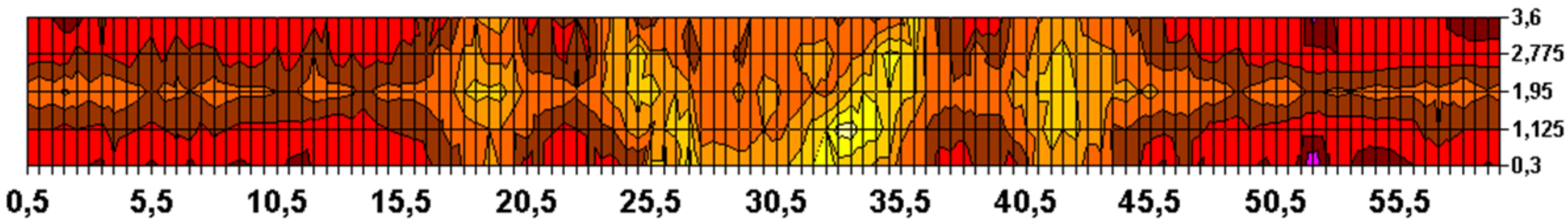
FSW Classification

$$\begin{cases} \bullet\ \text{Hot} \Leftrightarrow \begin{cases} \uparrow \Omega \\ \downarrow v \end{cases} \Rightarrow \begin{cases} \uparrow \text{HAZ} \\ \downarrow \text{TMAZ} \end{cases} \\ \bullet\ \text{Cold} \Leftrightarrow \begin{cases} \downarrow \Omega \\ \uparrow v \end{cases} \Rightarrow \begin{cases} \downarrow \text{HAZ} \\ \uparrow \text{TMAZ} \end{cases} \end{cases}$$



Vickers Hardness Field

$$\frac{\Omega\,[\mathrm{rpm}]}{v\,[\mathrm{mm/min}]} = \frac{1600}{800} = 2$$



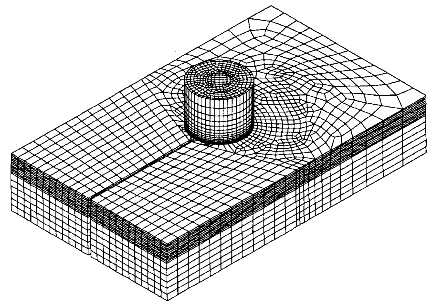
Courtesy of HZG

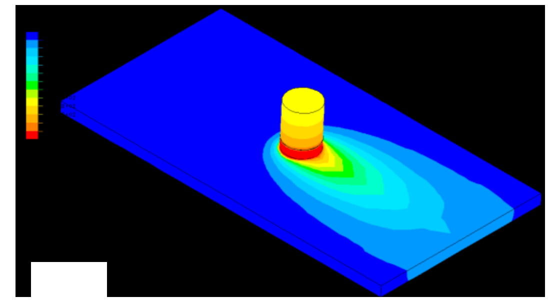
Fundaments of Modelling

Modelling Structure

$$\underbrace{\rho c_p\left(\frac{\partial T}{\partial t}+v_x\frac{\partial T}{\partial x}+v_y\frac{\partial T}{\partial y}+v_z\frac{\partial T}{\partial z}\right)}_{\text{Internal Energy Balance}}=$$

$$\underbrace{k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\frac{\partial k}{\partial T}\left[\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2+\left(\frac{\partial T}{\partial z}\right)^2\right]+A}_{\text{Energy Flow In - Energy Flow Out}}$$





Formulation | Discretization | Solution

Physical Model → Mathematical Model → Discrete Model → Discrete Solution

Solution Error

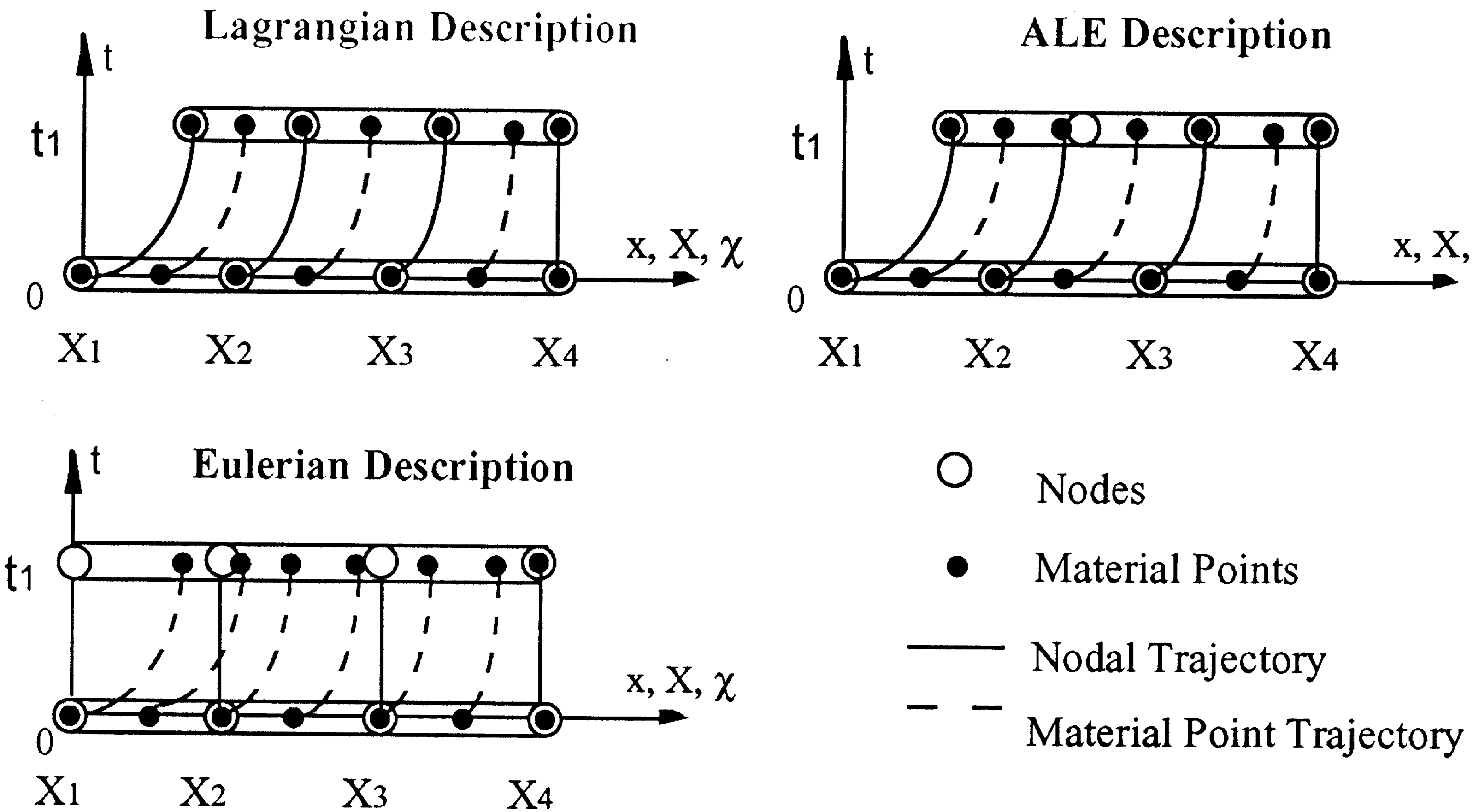
Discretization Error + Solution Error

Formulation Error + Discretization Error + Solution Error

Verification and Validation

Fundaments of Modelling

Formulation Methods



Fundaments of Modelling

Discretization Methods

Discretization

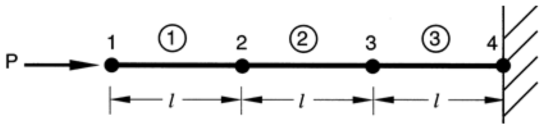
Mathematical Model → Discrete Model

- Finite Element Method
- Finite Difference Method
- Finite Volume Method
- Meshless Method (SPH)

Fundaments of Modelling

Integration Methods

Implicit	Explicit



$$\underbrace{\int_V f.\delta v dV}_{body.force} = \underbrace{\int_V P.\delta v dV}_{external.force} - \underbrace{\int_V \rho\ddot{u}.\delta v dV}_{d'Alembert.force}$$

virtual work equation

$$\ddot{u} = M^{-1}(P-I)$$

system of nonlinear equilibrium equations

Implicit

Newmark formulae

$$\dot{u}_{t+\Delta t} = \dot{u}_t + \Delta t((1-\gamma)\ddot{u}_t + \gamma\ddot{u}_{t+\Delta t})$$

$$u_{t+\Delta t} = u_t + \Delta t\dot{u}_t + \Delta t^2\left(\left(\frac{1}{2}-\beta\right)\ddot{u}_t + \beta u_{t+\Delta t}\right)$$

$$\beta = \frac{1}{4}(1-\alpha)^2 \quad ; \quad \underbrace{-\frac{1}{3} \le \alpha \le 0}_{material.damping.parameter} \quad ; \quad \gamma = \frac{1}{2} - \alpha$$

residual $\rightarrow 0 \Rightarrow$ ***iteration convergence***

$$R_{t+\frac{\Delta t}{2}} = M\ddot{u}_{t+\frac{\Delta t}{2}} + (1+\alpha)\left(I_{t+\frac{\Delta t}{2}} - P_{t+\frac{\Delta t}{2}}\right) - \frac{1}{2}\alpha\left(I_t - P_t + I_{t^-} - P_{t^-}\right) + L_{t+\frac{\Delta t}{2}}$$

Explicit

Central difference integration rule

$$\dot{u}_{t+\frac{\Delta t}{2}} = \dot{u}_{t-\frac{\Delta t}{2}} + \frac{\Delta t_{t+\Delta t} + \Delta t_t}{2}\ddot{u}_t$$

$$u_{t+\Delta t} = u_t + \Delta t_{t+\Delta t}\dot{u}_{t+\frac{\Delta t}{2}}$$

stable time increment

$$\Delta t_{stable} = \frac{L}{C_d}$$

M – *mass matrix* P – *external force vector* I – *internal force vector*

u – *displacement vector* $\dot{u}$ – *velocity vector* $\ddot{u}$ – *acceleration vector*

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)

FE Mesh

Integration

- Pressure
- Temperature

Updated at interface :
- Temperature
- Pressure

Fluid Dynamics Approach
(E.g. Fluent)

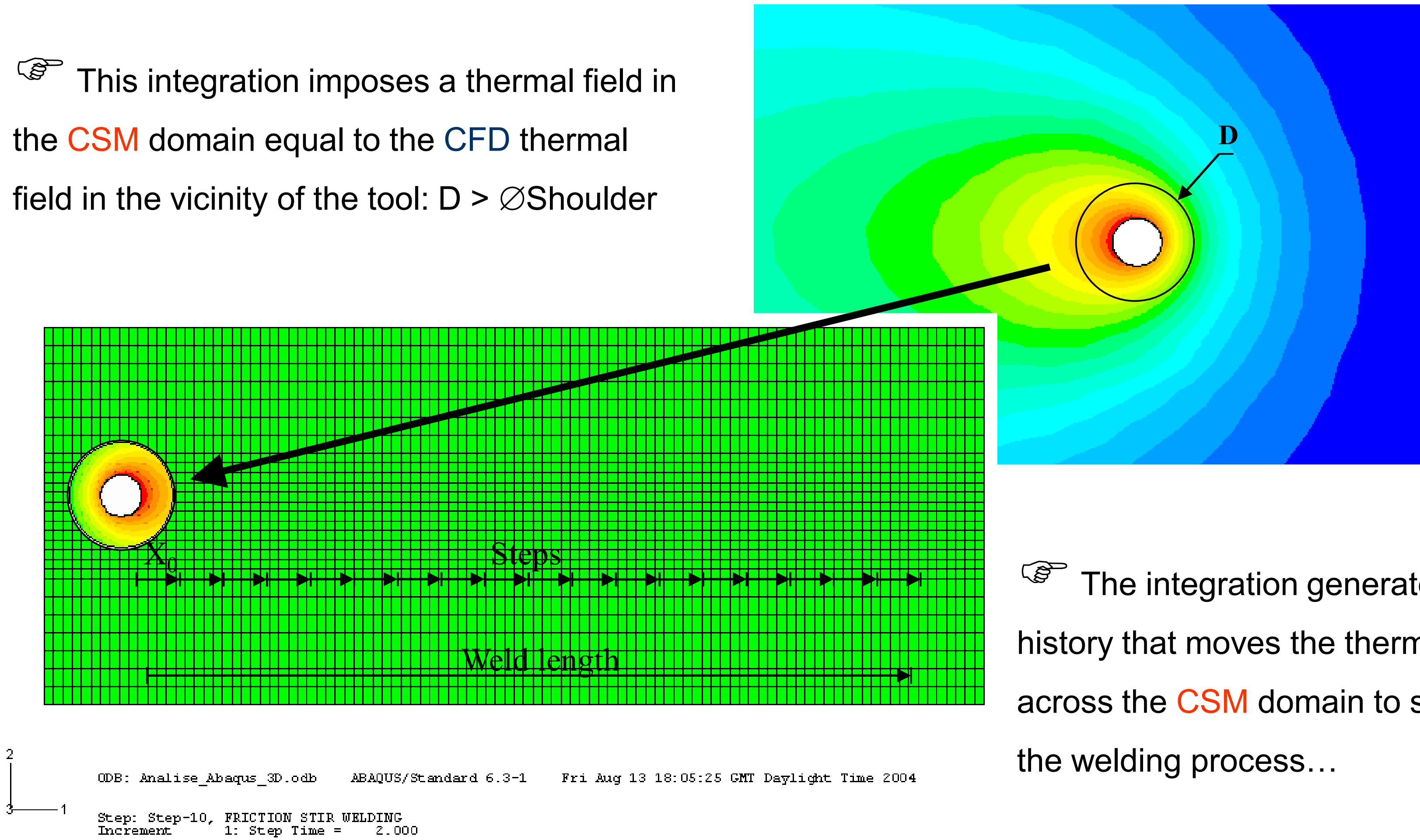
Results
Residual Stress Field
Residual Deformation
Thermal History of the HAZ

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

Example of Numerical Modelling Approach

Description of the Integration CSM / CFD

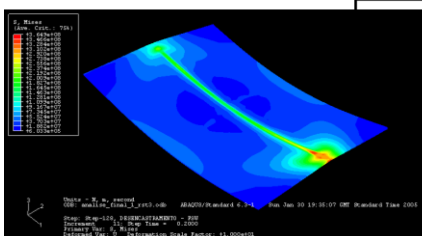
☞ This integration imposes a thermal field in the CSM domain equal to the CFD thermal field in the vicinity of the tool: D > ∅Shoulder



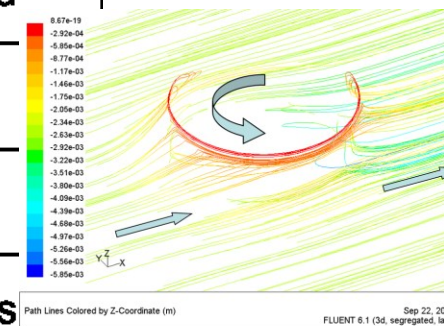
☞ The integration generates an history that moves the thermal field across the CSM domain to simulate the welding process…

Example of Numerical Modelling Approach

Features of the Integration CSM / CFD



Computational Solids Mechanics (CSM)	Computational Fluid Dynamics (CFD)
Finite Element Method	Finite Volume Method
Implicit Integration Scheme	
Thermo-Mechanically Coupled Analysis	
Transient Regime	Steady-State Analysis
Lagrangean Analysis	Eulerian Analysis
Elastic-Plastic Temperature Dependent Material Model	Viscous-Plastic Material Model (Zenner-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:

$$\dot{\varepsilon}_{ij} = \frac{1}{2\eta} S_{ij} \qquad S_{ij} = \sigma_{ij} - \delta_{ij} p \qquad p = \frac{\sigma_{ii}}{3}$$

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: $$\eta\left(T, \dot{\bar{\varepsilon}}\right) = \frac{S\left(T, \dot{\bar{\varepsilon}}\right)}{3\ \dot{\bar{\varepsilon}}}$$

where: $\dot{\bar{\varepsilon}} = \sqrt{\frac{2}{3} \dot{\varepsilon}_{ij} \dot{\varepsilon}_{ij}}$ – Effective strain rate

$S\left(T, \dot{\bar{\varepsilon}}\right)$ – Effective deviatory flow stress

Material Modelling for CFD

Zener-Hollomon Model

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

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

where: T – Absolut 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:

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

where: - A, α, n are fitting constants

Material Modelling for CSM

Elastic-Plastic Material with Thermal Expansion

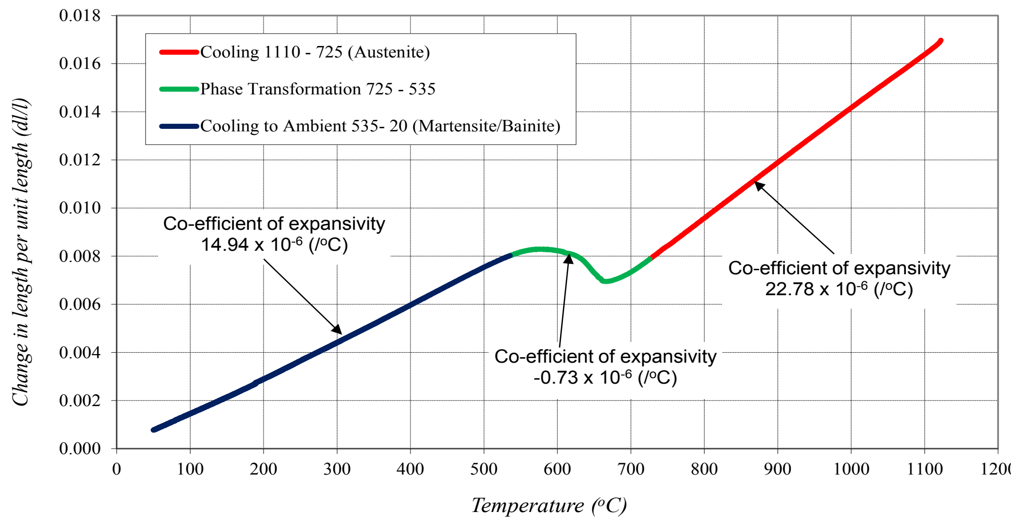
Solid Mechanics
Thermo-Mechanical Analysis: $\varepsilon^{thermal} = \alpha_{expansion} \Delta T \Rightarrow \sigma = E\left(\varepsilon - \varepsilon^{thermal}\right)$

E=73 GPa ; ν=0.33				
Mechanical Properties at Elevated Temperatures				
Temp. [K}	Time at Temp. [h]	YTS [MPa]	UTS [MPa]	Elong %

Temp. °C	$\alpha_{expansion}$ [m/m.K]

Thermal Properties Depending on Temperature	
K (T) [W/m.K]	Cp (T) [J/Kg.K]

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



Modelling of Friction Stir Welding

Final Remarks

- ☞ Highly non-linear character (geometric, material, formulation)
- ☞ Physical properties vary throughout the FSW process ⇔ 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

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Thank You

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