COMSOL CONFERENCE 2015 PUNE

N
M
R
L

Modeling of Residual Stresses in a Butt-welded Joint with Experimental Validation

Vivek Srivastava & AG Rao

Naval Materials Research Laboratory (NMRL), Thane
Defence Research & Development Organization (DRDO)

COMSOL Conference 2015, Pune

Outline

- Structural Integrity: Role of Residual Stresses (RS)
- Residual Stress: Origin and Distortion Effect
- Welding Residual Stress Effect on Fatigue Life
- Problem Description : Modeling of RS in Butt-weld joint
- COMSOL Multiphysics Model Description: Thermal & Structural Mechanics
- Simulation Results & Experimental Validation
- Concluding Remarks

N
M
R
L

Structural Integrity

– science & technology of margin between safety & disaster

N M R L

Key Aspects

- Structural Analysis
- Failure Analysis
- Creep Analysis
- Structural Monitoring & Instrumentation
- Software Development for Life Time Assessment
- Non destructive testing
- Fracture Mechanics
- Fatigue Analysis & Assessment
- Corrosion
- Welding Metallurgy
- ***Residual Stress Analysis***

Residual Stress Analysis

Caused by Thermo-mechanical Processing of steel

- Mechanical factors – alter physical shape
  - Machining, Forging, Rolling, Drawing
- Thermal factors – induce temperature gradient
  - Welding, Casting, Quenching

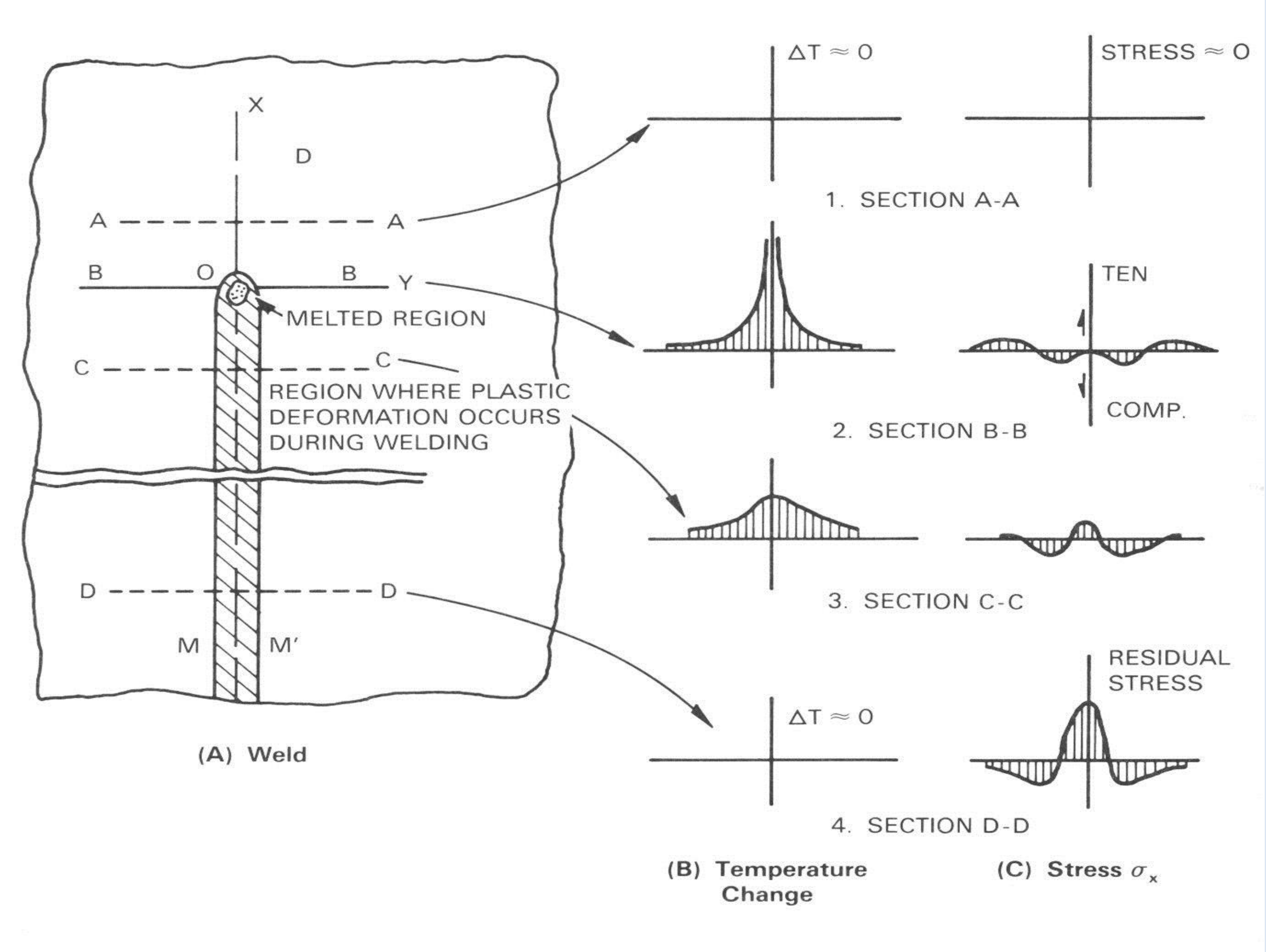
Measurement Techniques :

- Destructive – Sectioning, Contour methods
- Semi-destructive – Hole Drilling method
- Non-destructive – X-ray diffraction, Neutron diffraction & Magnetic Noise method

Role of Fracture Mechanics

- Linear Elastic Fracture Mechanics – Stress Intensity Factor (K), Crack tip plasticity, Modes of Fracture, Plane Strain Fracture Toughness
- Elastic-Plastic Fracture Mechanics – CTOD & J-integral
- **Fatigue Design /Life Assessment – Initiation** & Propagation
- Environment Assisted Cracking in metals – Stress corrosion, Hydrogen Embrittlement, Corrosion Fatigue
- Fracture Mechanisms - Brittle, Ductile, Cleavage, Trans-granular, Intergranular

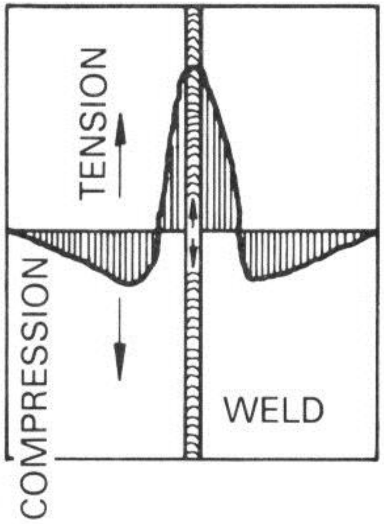
Residual Stress Evolution during Welding



Residual Stress & Distortion in Welds

N M R L

- *Heat flows from the weld area and causing the joint area to expand*
- *Thermal expansion and contraction due to welding can leave behind permanent stress and distortion*
- *Higher heat input welds are more prone to residual stress and distortion*
- *Increased restraint can decrease distortion but can result in higher residual stress*



(B) Residual Stresses Due to Welding

0.1.1.3.3.T18.95.12

Fatigue Life Assessment (FLA) Methodology of Structures (based on Fracture Mechanics)

N M R L

Driving Force

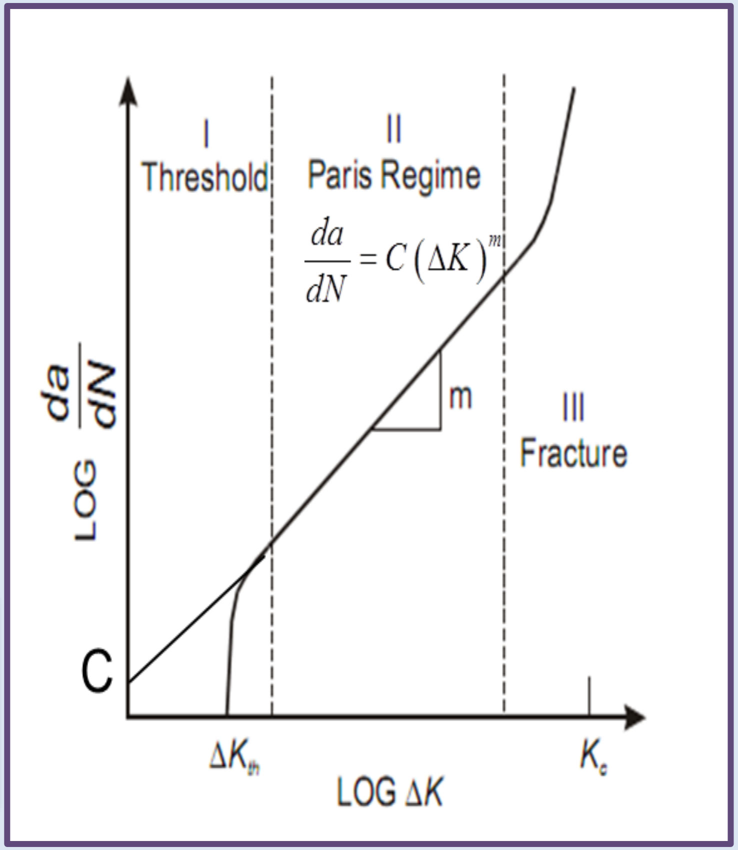
Stress Intensity Range: $\Delta K = Y \Delta \sigma \sqrt{\pi a}$

Where,

$\Delta\sigma = \sigma_{max} - \sigma_{min}$

Y = structural geometric correction factor (dimensionless); determined by FEA

a = ***damage variable*** (crack length)



Response Variable

Incremental Damage per cycle for stable FCP regime II i.e. ***Paris Regime***:

$$\frac{da}{dN} = C(\Delta K)^m$$

Predicted Fatigue Life of Structure

Predicted Life of Naval structure i.e. ***number of corrosion fatigue cycles*** (from initial damage, a_i to critical damage, a_{CR}) :

$$N = \int dN = \int \frac{da}{C(\Delta K)^m} = \int_{a_i}^{a_{CR}} \frac{da}{C Y^m \Delta\sigma^m (\pi a)^{m/2}}$$

Fatigue Life of Weld Joints: Effect of Residual Stresses

NMRL

Residual Stresses ($\sigma_{RESIDUAL}$) in a Structure

modify :

- Effective Stress Intensity Factor (K)
- Load Ratio (R)
- Governing Paris Equation **>>** ***Walker's Equation***
- Fatigue Life of the Structure

Barsoum Z et al, Eng Fail Anal (2008)

Flow Chart for Incorporating Residual Stresses into Fatigue Life Assessment

$$K_{RESIDUAL} = Y \sigma_{RESIDUAL} \sqrt{\pi a}$$

$$K_{eff}^{min} = K_{applied}^{min} + K_{RESIDUAL}$$

$$K_{eff}^{max} = K_{applied}^{max} + K_{RESIDUAL}$$

$$R_{eff} = \frac{K_{eff}^{min}}{K_{eff}^{max}} = \frac{K_{applied}^{min} + K_{RESIDUAL}}{K_{applied}^{max} + K_{RESIDUAL}}$$

$$\frac{da}{dN} = \frac{C(\Delta K)^m}{(1 - R_{eff})}$$

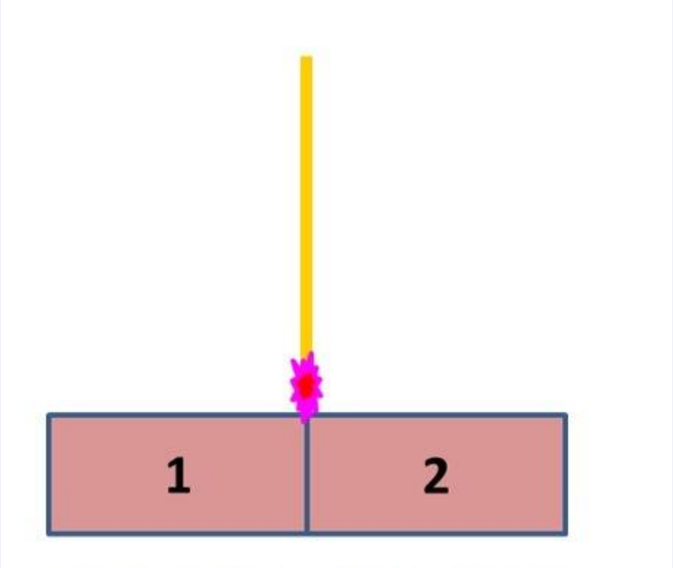
$$N = \int dN = \int_{a_i}^{a_{CR}} \frac{(1 - R_{eff})}{C(\Delta K)^m} da$$

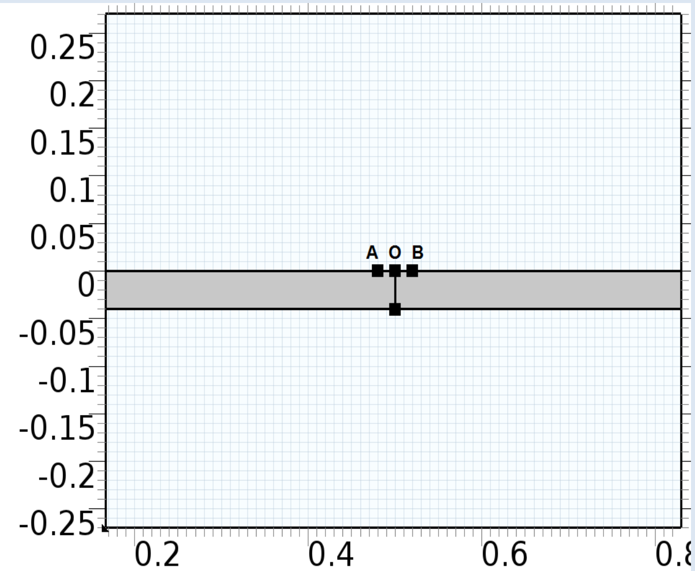
Problem Description : Modeling of RS in Butt-weld Joint

N
M
R
L

- ***Two HSLA steel plates were weld simulated***
- ***Geometry was 2D-modeled***
- ***Weld electrode arc contact occurred with a circular span radius of 1.5 mm***
- ***This arc contact area used for calculating the input surface heat flux***

Parameter	***Value***
Plates	1 and 2
Material	Structural Steel
Weld Joint Type	Butt
Weld Pre-Heat / Interpass Temperature	150 ^{o}C (423 ^{o}K)
Heat Input	1.5 kJ / mm





COMSOL Multiphysics Model Description: Thermal Behavior (Heat Transfer Module)

N M R L

- ***Heat source*** *modeled as a surface heat flux following Gaussian distribution*
- ***Calculated Surface Heat Flux*** *from weld heat input, weld speed and contact length:* ***5e8 W/m²***
- ***Prediction of temperature field*** *required for determining plastic strains and welding residual stresses*
- ***Conductive heat transfer*** *with phase change*
- ***Convective heat transfer*** *with appropriate BCs applied on the open surfaces of the geometry except arc contact length AOB*

Parameter / IC / BC	***Value***
Material Thermo-physical Properties	*Structural Steel*
Liquidus temperature of the steel	*1790 K*
Latent Heat of Fusion	*245 KJ/Kg*
Convective heat transfer coefficient	*50 W/m^2-K*
IC: Initial temperature (weld pre-heat / inter-pass temperature)	*150 °C (423 K)*
BC: Ambient temperature	*25 °C (298 K)*

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q + Q_{vh} + W_p$$

$$k = \theta k_{phase1} + (1-\theta) k_{phase2}$$

$$C_p = \theta C_{p.phase1} + (1-\theta) C_{p.phase2} + L \frac{d\alpha}{dT}$$

$$\rho = \frac{\theta \rho_{phase1} C_{p.phase1} + (1-\theta) \rho_{phase2} C_{p.phase2}}{\theta C_{p.phase1} + (1-\theta) C_{p.phase2}}$$

$$-\mathbf{n} \cdot (-k \nabla T) = h \cdot (T_{ext} - T)$$

COMSOL Multiphysics Model Description: Structural Behavior (Solid Mechanics Module)

N M R L

- *Linear Elastic material domain selected with* ***constitutive stress-strain behavior with thermal effect***
- ***Thermal elastic-plastic behavior*** *described by a plasticity model based on* ***Von Mises yield criteria*** *and* ***isotropic hardening model***
- *Zero values of initial stress, strain, displacement and structural velocity fields were* ***initial conditions***
- ***Restrained welding configuration*** *during the course of this study, prescribed displacement in vertical direction were put to zero ($u_y = 0$) as a* ***boundary condition***
- ***Fully Coupled with Heat Transfer Module***

$$-\nabla \cdot \sigma = F_V, \quad \sigma = s$$

$$s - S_0 = C : (\epsilon - \epsilon_0 - \epsilon_{inel})$$

$$\epsilon = \frac{1}{2}\left[(\nabla u)^T + \nabla u\right]$$

$$s - S_0 = C : (\epsilon - \epsilon_0 - \epsilon_{inel}), \quad \epsilon_{inel} = \epsilon_p$$

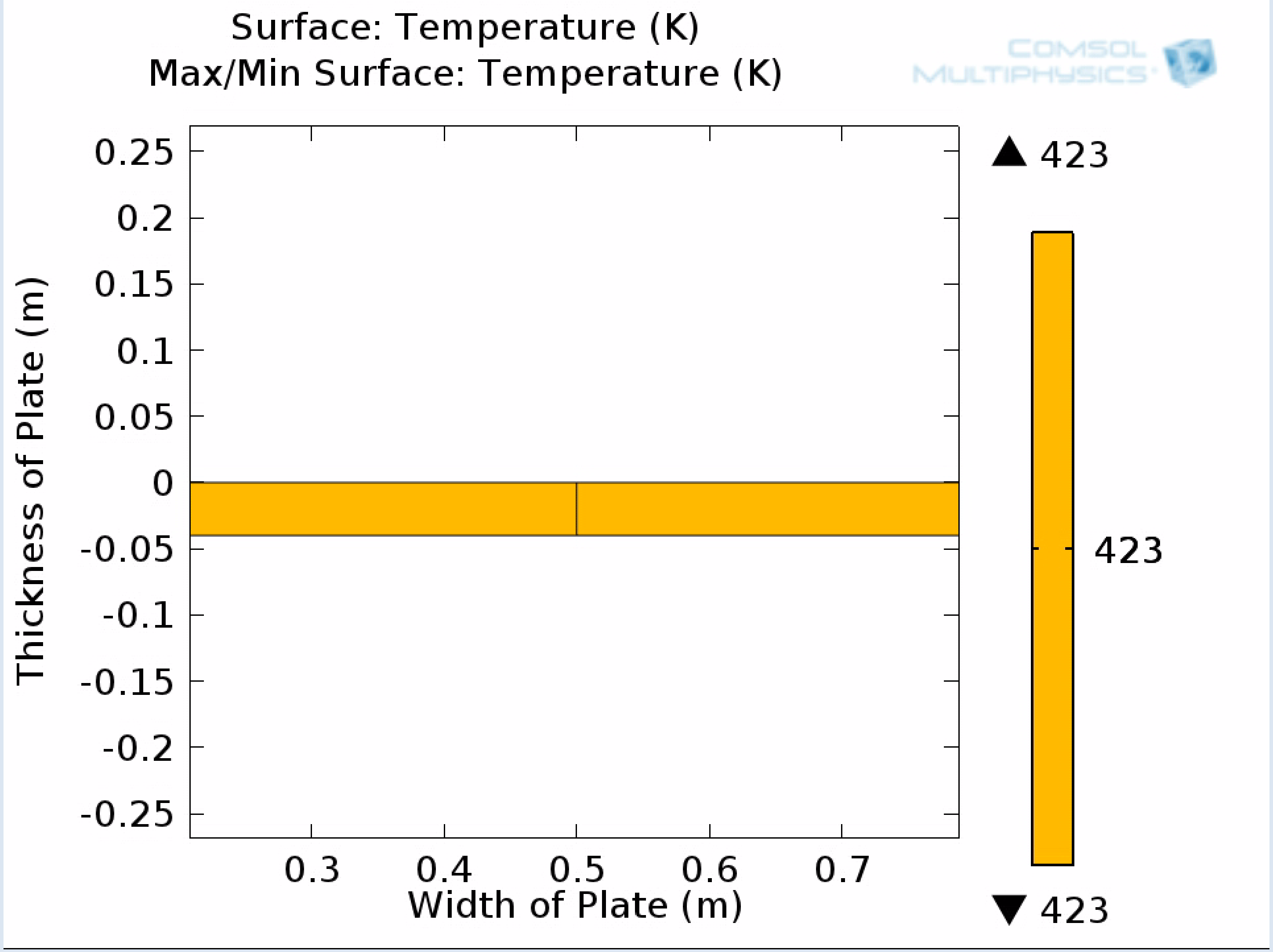
$$F(\sigma, \sigma_{ys}) \leq 0, \quad \dot{\epsilon}_p = \lambda \frac{\partial Q}{\partial \sigma}$$

$$F = \sigma_{mises} - \sigma_{ys}, \quad Q = F$$

$$\sigma_{ys} = \sigma_{ys0} + \frac{E_{Tiso}}{1 - \frac{E_{Tiso}}{E}} \epsilon_{pe}$$

$$\epsilon_{th} = \alpha(T - T_{ref})$$

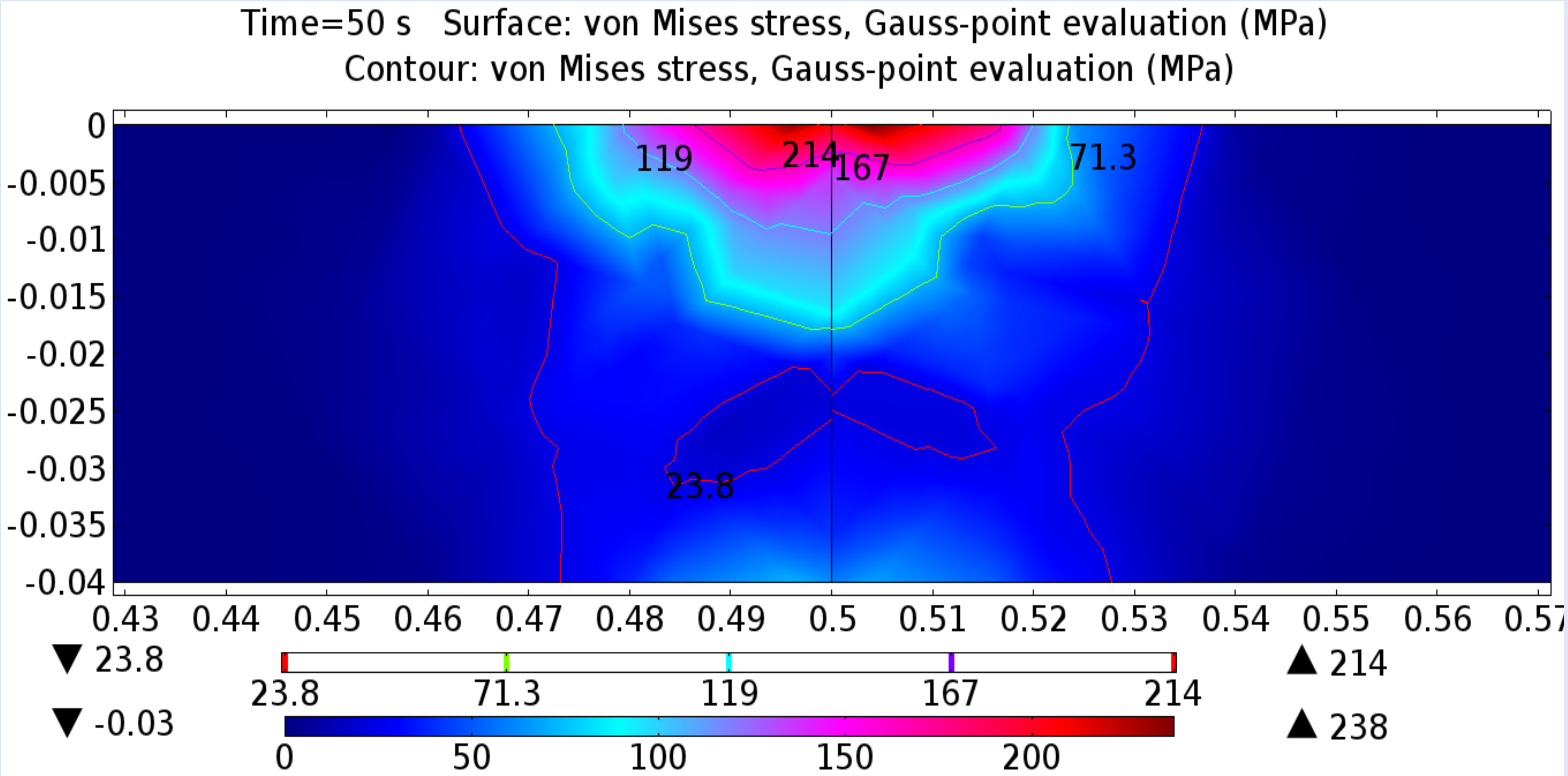
Weld Simulation Results – Temperature Field Evolution in Fusion Zone



N M R L

Weld Simulation Results – Residual Stress Mapping

N M R L



Experimental Validation of 2D Butt-weld Model for Residual Stress Prediction

NMRL

Depth (mm)	Residual Stress (Simulation) – COMSOL	Residual Stress (Experimental) – XRD	Percentage Deviation (%)
10	116.1	100.8	15.2
20	65.3	73.5	11.2
30	32.1	34	5.6

- *Close agreement (within 15 %) between the simulated and experimental values of in-situ residual stresses*
- *Validation of the accuracy of COMSOL simulated FEM model of the studied butt-weld joint*

Concluding Remarks

N M R L

- *In this study, complex multi-physical phenomenon of* ***arc welding for a butt-joint configuration was 2D-modeled using COMSOL***
- *Inward surface heat flux from weld electrode arc, conductive and convective heat transfer with appropriate initial and boundary conditions were applied to describe the* ***temperature evolution within the fusion zone*** *and plates*
- *Further* ***constitutive stress-strain behavior was solved with thermal-elastic-plastic effect*** *using a plasticity model based on Von Mises stress and isotropic hardening.*
- *Steady state solution achieved for final state of the stress was the measure of* ***residual stresses distribution*** *across thickness-oriented plane of a butt-welded joint of an HSLA steel.*
- ***Experimental validation*** *of the above model was performed by measuring residual stresses using* ***X-Ray Diffraction (XRD) method***
- ***Close agreement (within 15 %)*** *between the simulated and experimental values of in-situ residual stresses was found* ***validating the accuracy of COMSOL simulated FEM model of the studied butt-weld joint***

N
M
R
L

Thank You

Questions ?