SAE FD&E
Welding Residual Stress Simulation Results & Process & Opportunities

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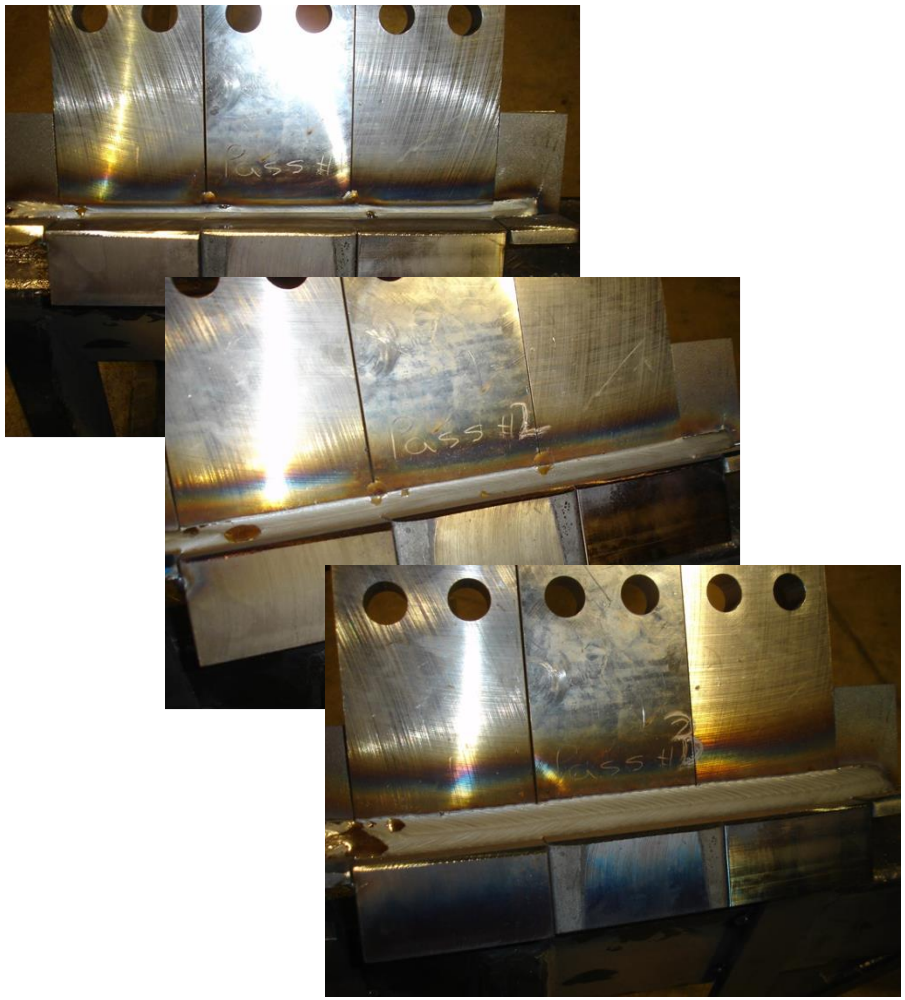
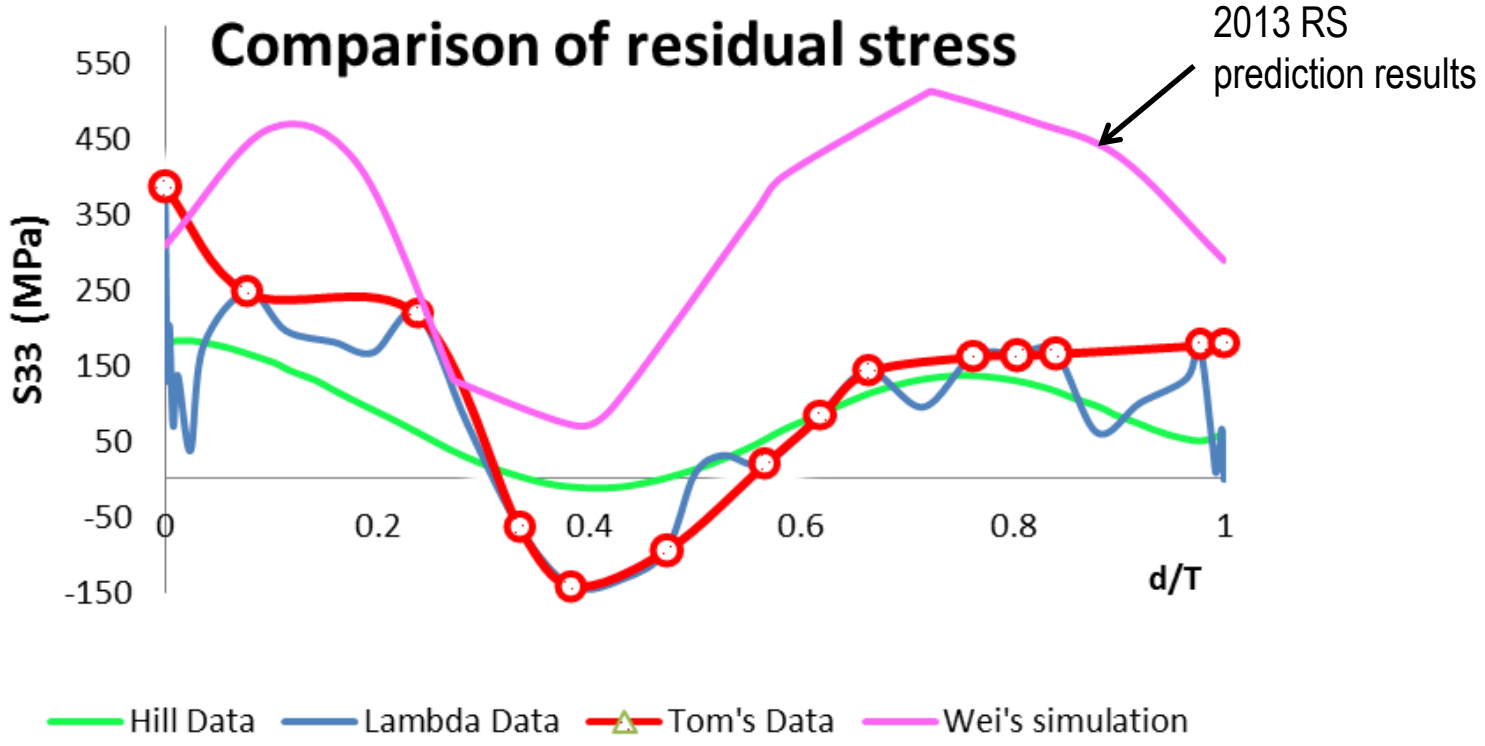
2015-05-06

Outline

- 2013 Background
- 2014 Samples
- 2014/2015 Simulation
- Weld Simulation Explanation
- Alternate XRD Opportunities
- Questions

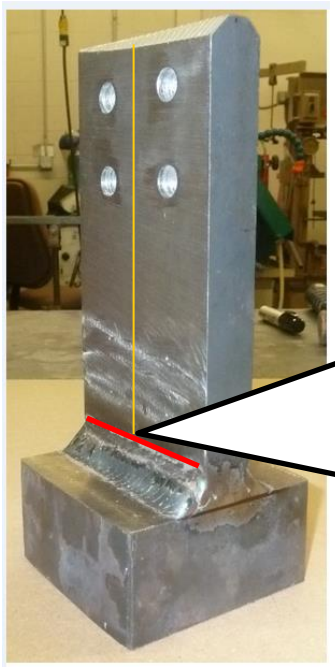


2013 Background



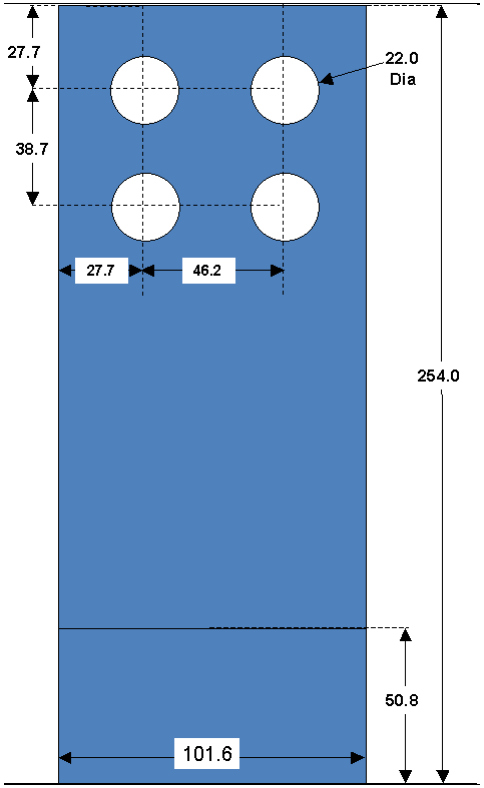
- Total Life Project, need Residual Stress (RS) state
  - Created/Simulated/Tested samples in 2013
- 2013 RS simulation correlation promising, but many unknowns
  - New samples created in 2014 with process recorded…

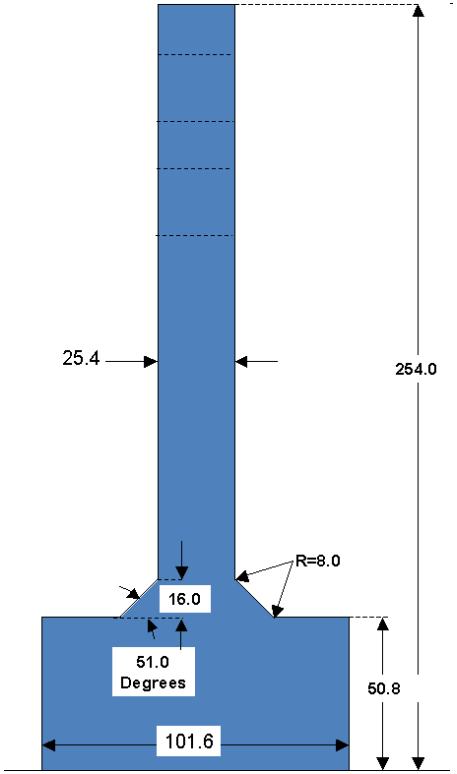
2014 Samples (Geometry)



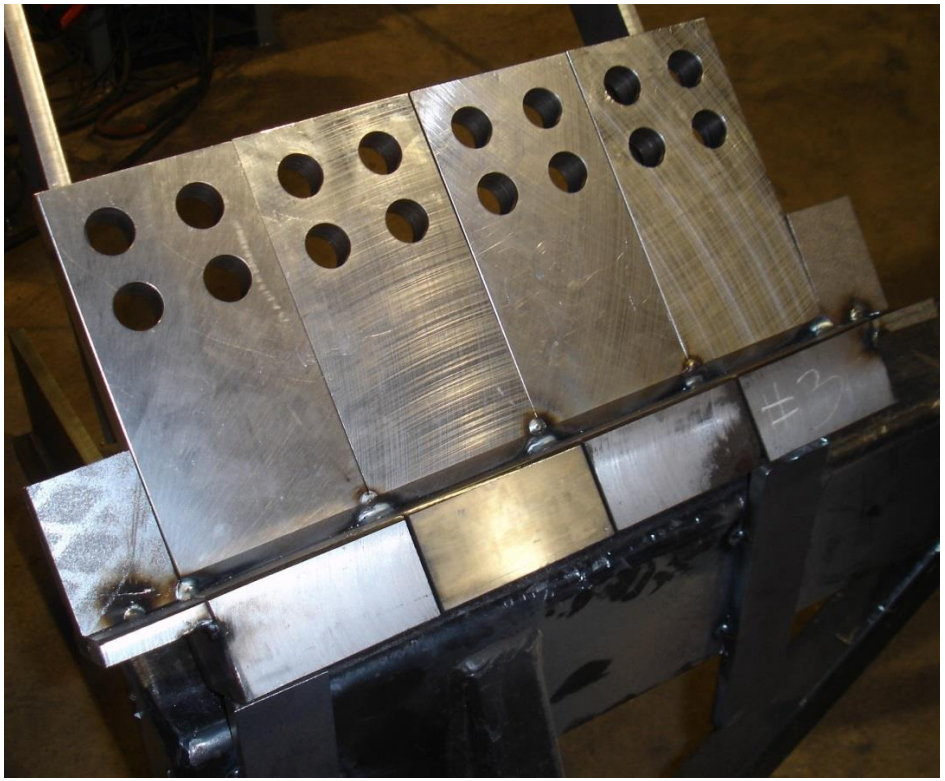
Investigate through-thickness residual stress at the weld toe & mid-plane, where maximum residual stress occurs.

Specimen





2014 Samples (Preparation & Fixture)



Samples were tack welded on both sides at the base. Runoff tabs were used at both ends. The parts were “free” in the “V” fixture. They were welded in groups of 3 and 4 (4 shown).

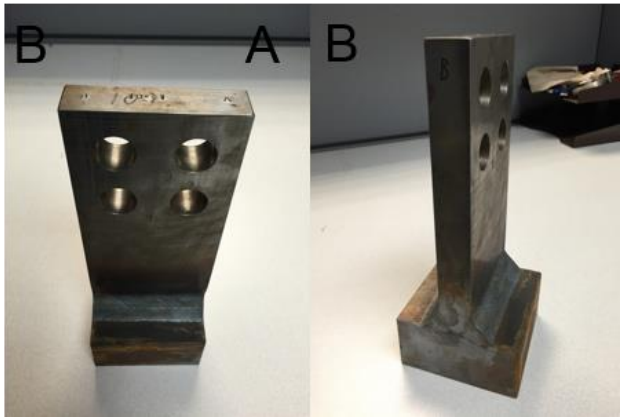
** Set up & Welding performed by SAE FD&E project members.*

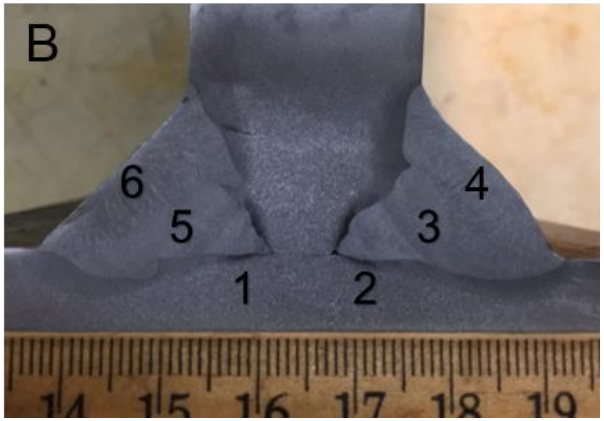
2014 Samples (Process Parameters)

Weld	Side	Starting End	Voltage	Current	Wire Speed	Travel Speed	Work Angle	Cooling Time*
1	1	A	38.5 V	235 A	7 m/min	40 cm/min	45	NA
2	2	B	38.5 V	235 A	7 m/min	40 cm/min	45	45 s
3	2	B	39.0 V	300 A	8 m/min	35 cm/min	45	3 s
4	2	B	39.5 V	225 A	8.5 m/min	60 cm/min	45	3 s
5	1	A	39.0 V	300 A	8 m/min	35 cm/min	45	1 m 30 s
6	1	A	39.5 V	225 A	8.5 m/min	60 cm/min	45	2 m 30 s

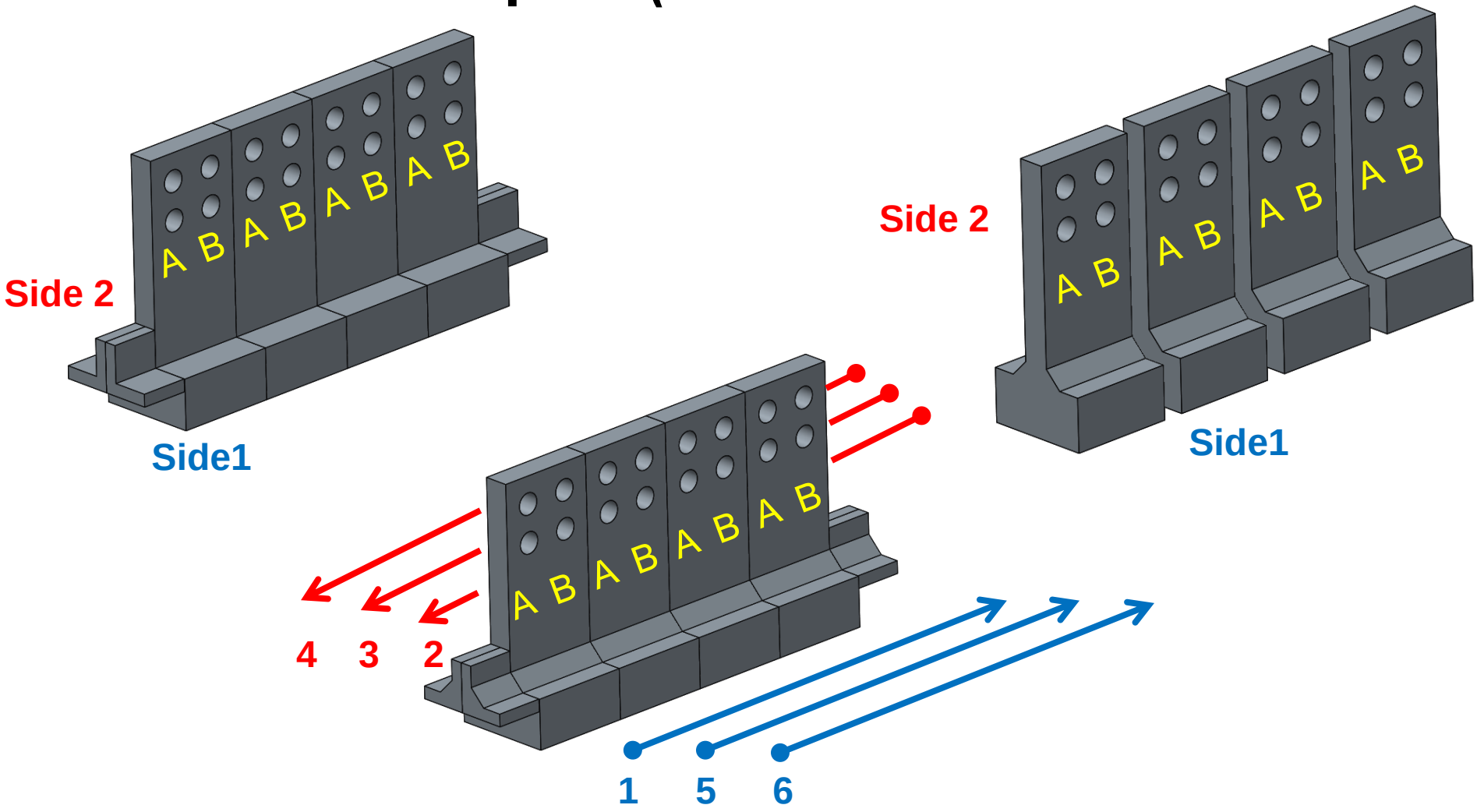
Parameter/Characteristic	Value
Welding Process	(GMAW)
Wire Type	(Solid)
Wire Diameter	0.062 inches
Shielding Gas	90% CO2/ 10% Ar
Base Material	A36
Filler Metal	ER70S-6
Welding Position	45 deg for all weld passes

** Tabular data was provided by SAE FD&E project members.*





2014 Samples (Process Animation)

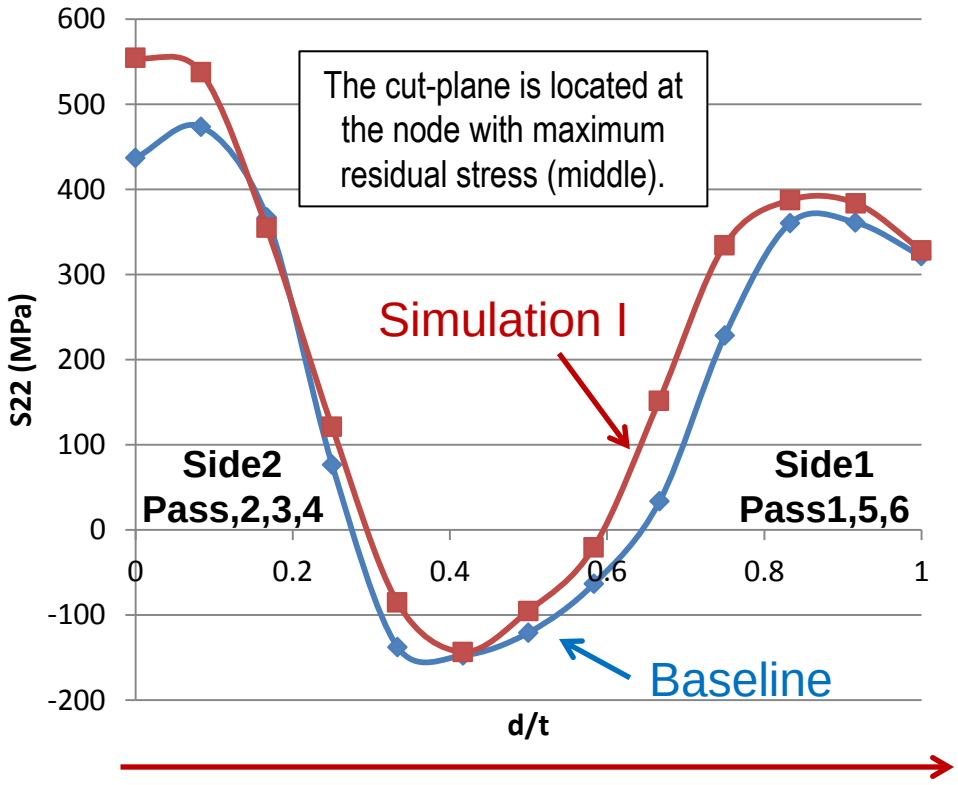


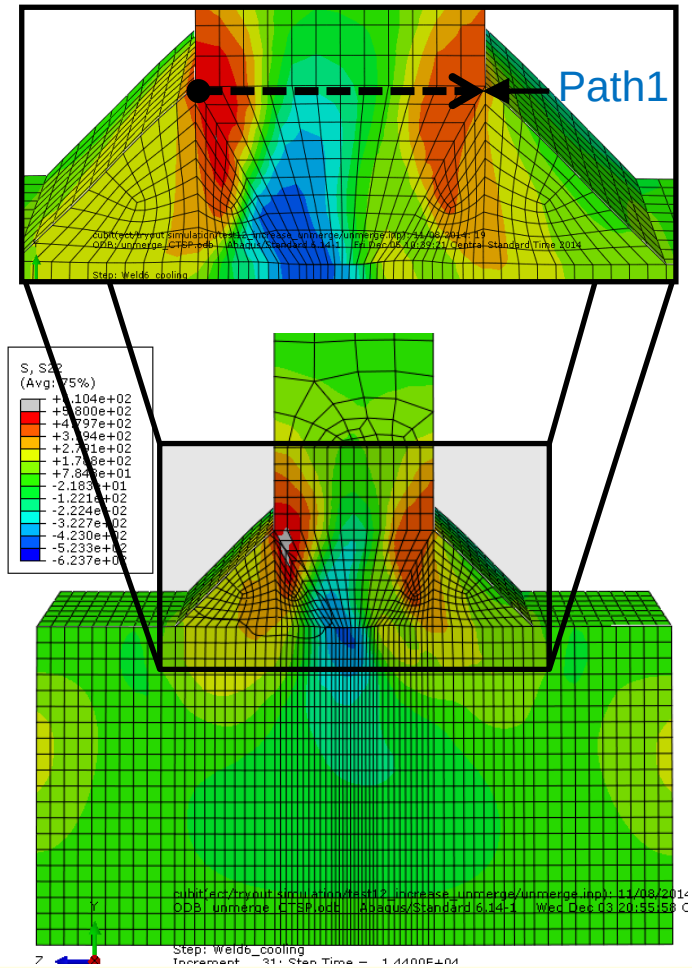
Simulation Assumptions

- **Geometry**
  - 1 sample for simplicity (3/4 possible if desired)
  - Weld modeled as perfect 45 deg triangle, sharp corners
  - No run off tabs
- **Weld Pass Shape Estimation**
  - Difficult due to inter-pass re-melting
  - Equal volume for all passes (from process parameters)
- **Fixture**
  - Parts “free” in saw horse fixture
  - 3 points to remove rigid body motion
- **Weld Process Parameters**
  - Power input and travel speed as provided
  - Cooling time: Arc Off Avg and Arc Off+On
- **Material Data (A36 Steel)**
  - Derived from Caterpillar proprietary data for mild steel
  - Derived from paper on World Trade Center steel

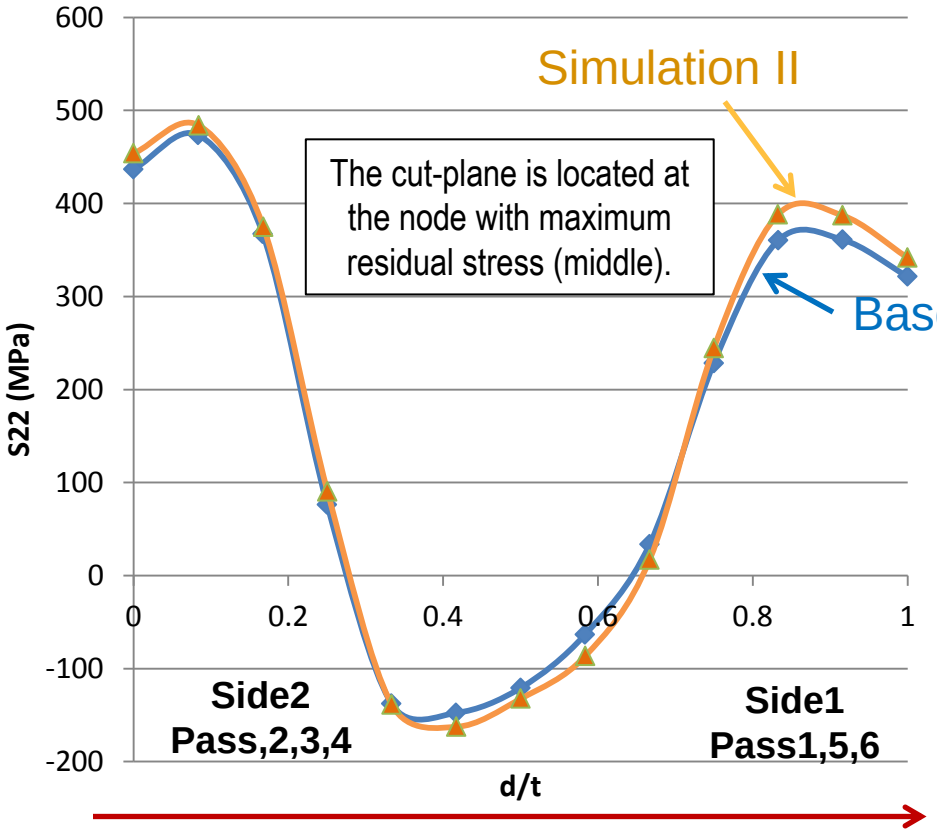
		2013 Caterpillar Simulation	2014 Caterpillar Simulation Baseline	2015 Caterpillar Simulation I	2015 Caterpillar Simulation II	2015 Caterpillar Simulation III
Physical	Samples	2013 Samples	2014 Samples			
	XRD Measurement	Lambda	Not Available	Not Available	Not Available	Not Available
	Contour Measurement	Hill Eng.	Not Available	Not Available	Not Available	Not Available
Virtual	Sample Count	1	1	1	1	1
	Weld Geometry	Sharp Triangle	Sharp Triangle	Sharp Triangle	Sharp Triangle	Sharp Triangle
	Runoff Tabs	No	No	No	No	No
	Weld Pass Volume	Equal	Equal	Equal	Equal	Equal
	Fixture	3 point	3 point	3 point	3 point	3 point
	Power Input	Guess	As Provided	As Provided	As Provided	As Provided
	Travel Speed	Guess	As Provided	As Provided	As Provided	As Provided
	Interpass Cooling Time	Guess	Arc Off Average	Arc Off Average	Arc Off+On	Arc Off+On
	Simulation Material	Caterpillar Proprietary	Caterpillar Proprietary	WTC	Caterpillar Proprietary	WTC

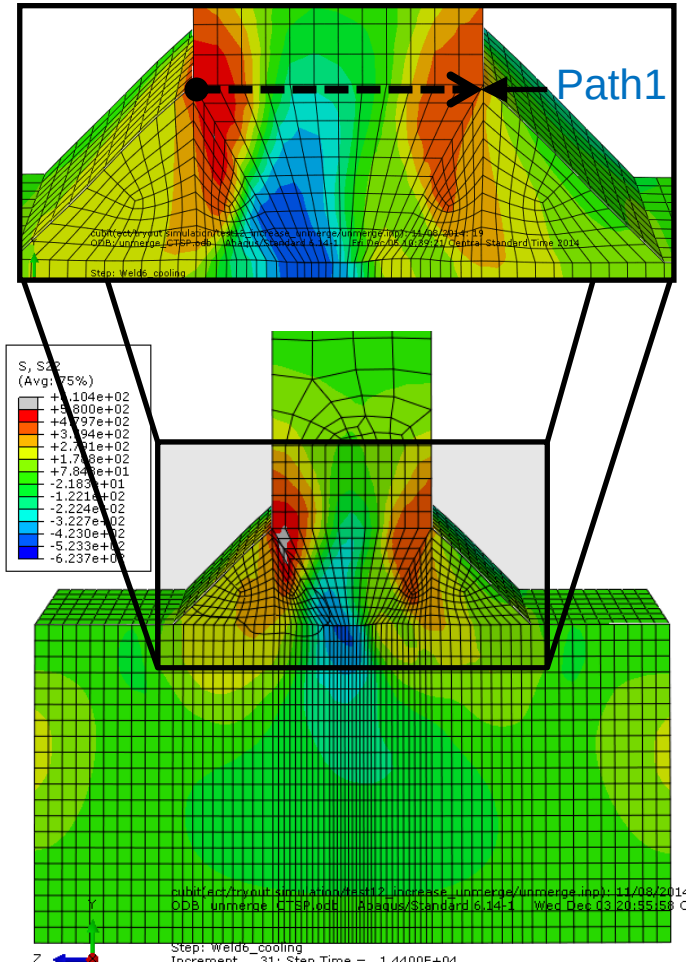
Baseline Vs. Simulation I (Material Property Effect)



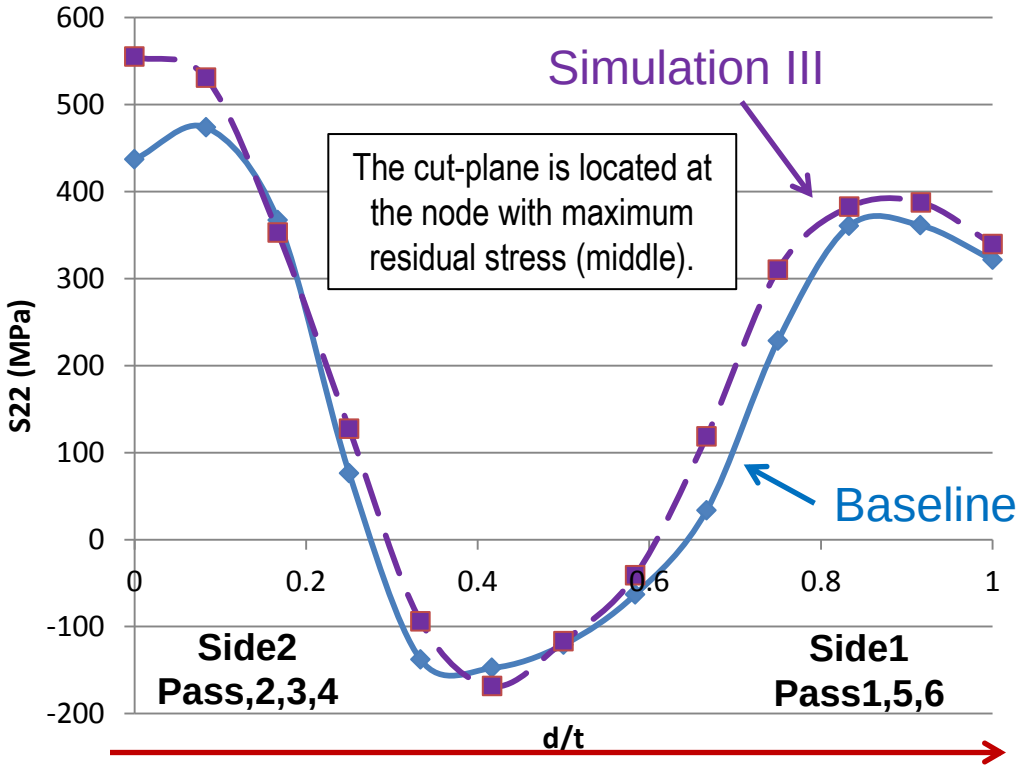


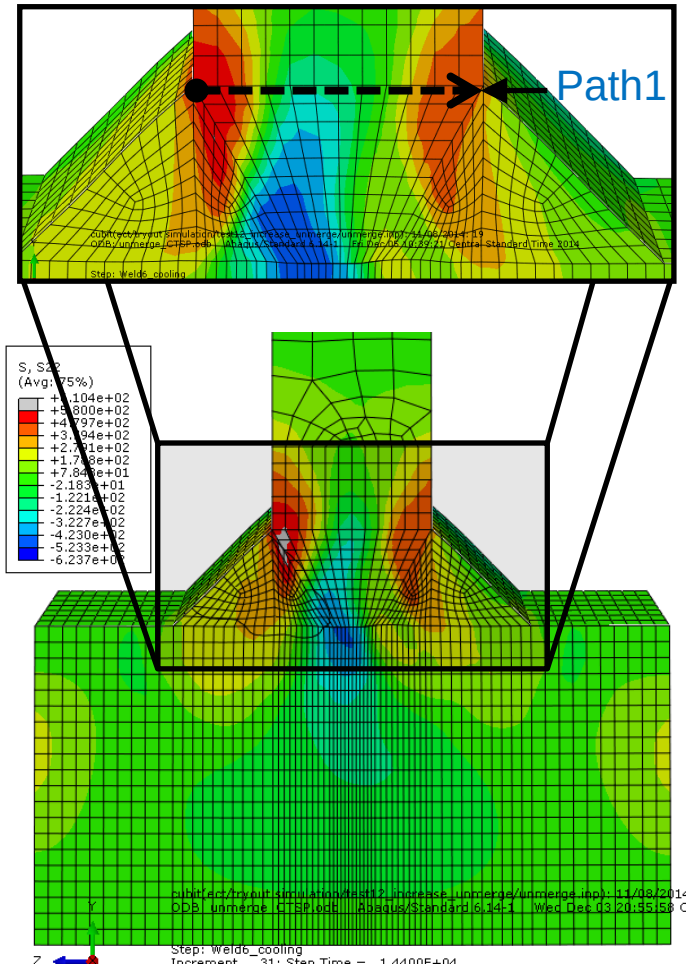
Baseline Vs. Simulation II (Cooling Time Effect)



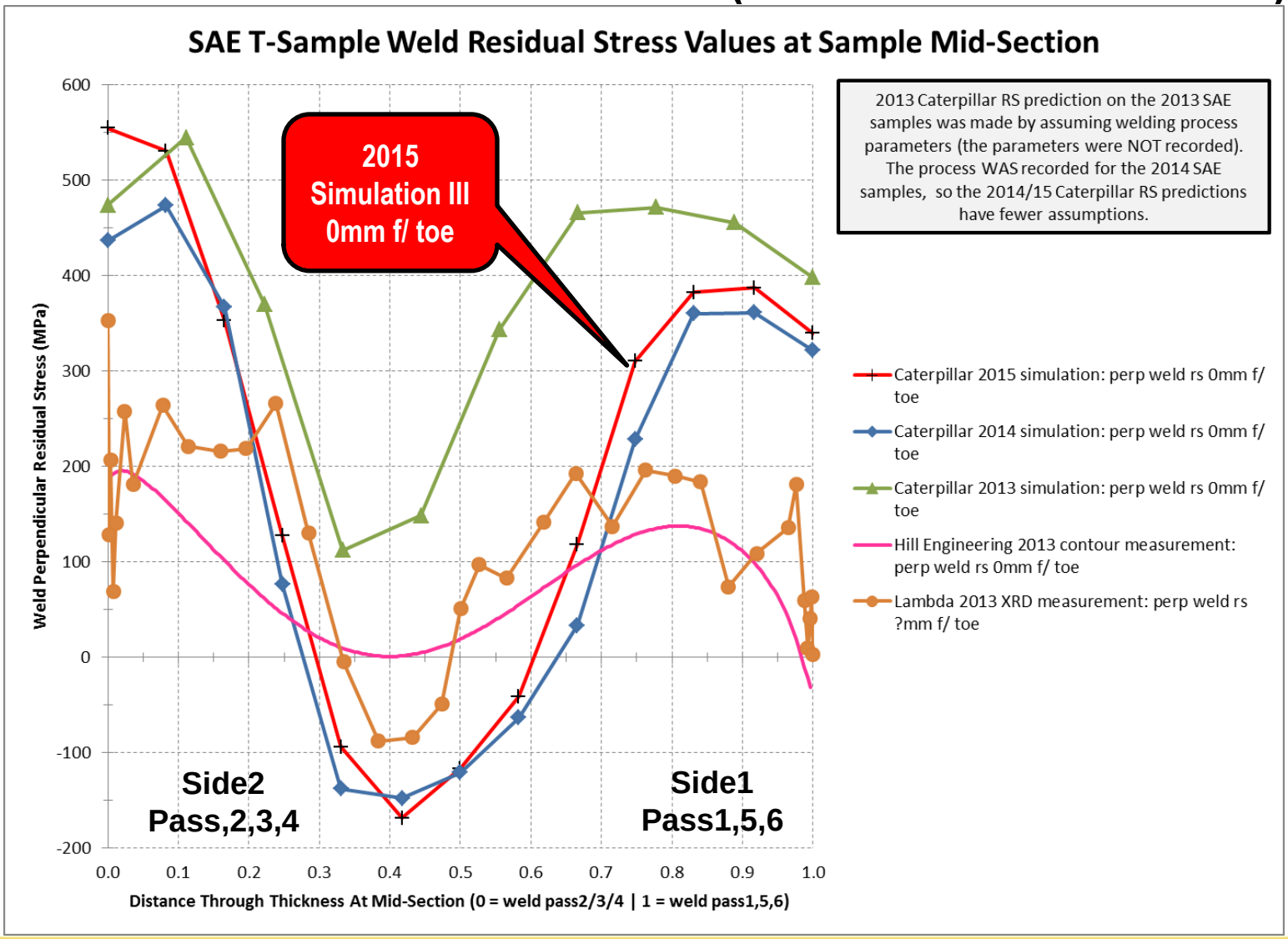


Baseline Vs. Simulation III (Material Property & Cooling Time Effect)

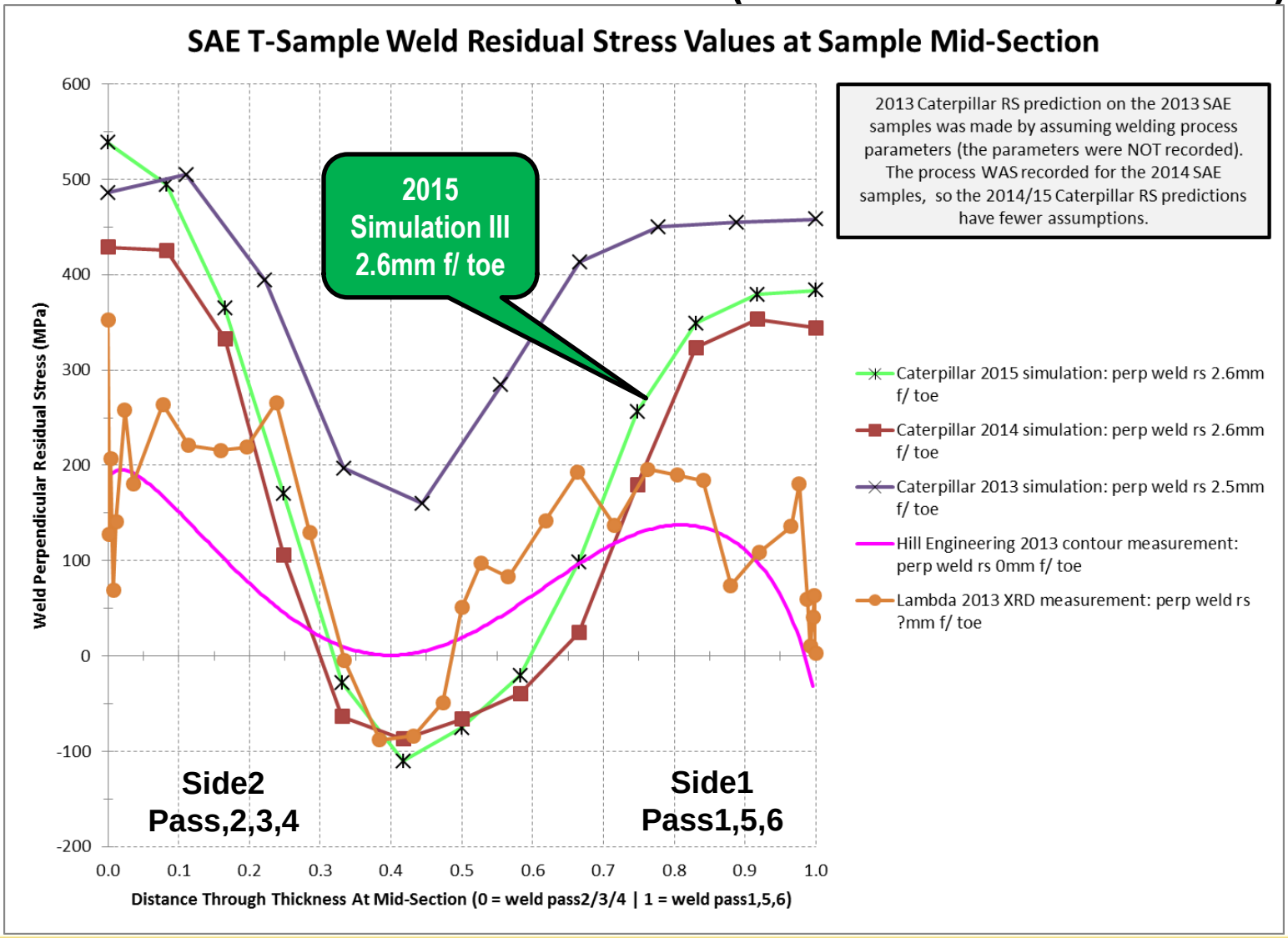




Final Residual Stress Results (0.0mm from Weld Toe)

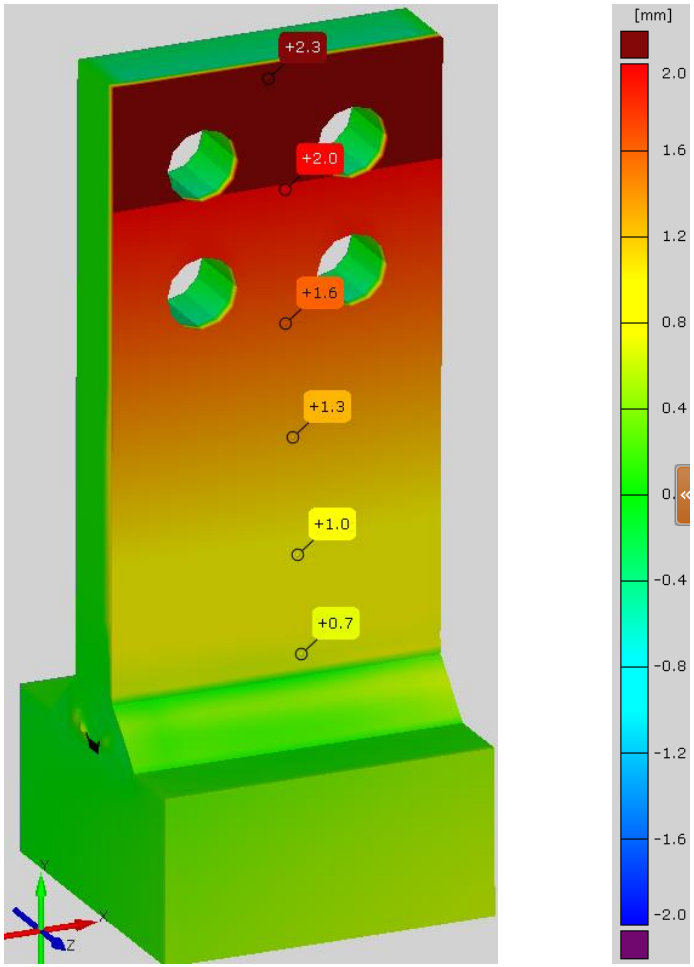


Final Residual Stress Results (2.6mm from Weld Toe)

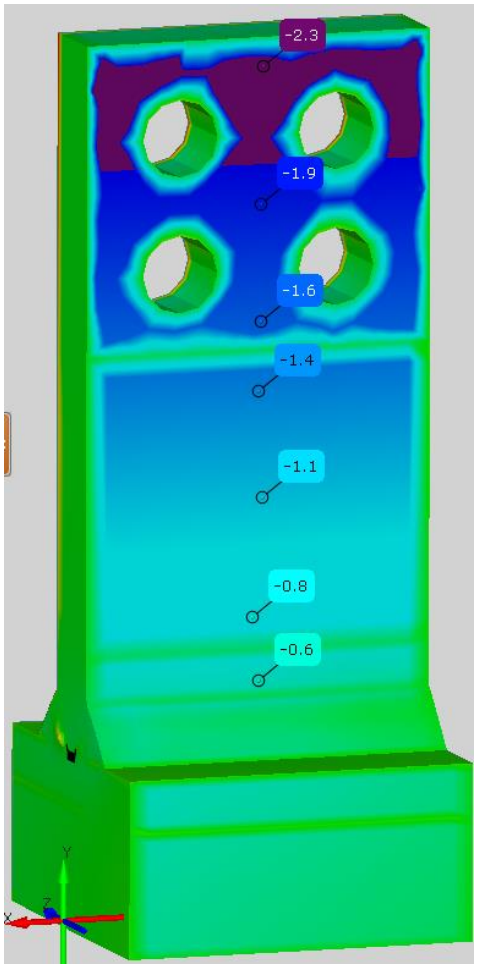


Simulation III Distortion (mm)

SIDE 2, Pass 2/3/4

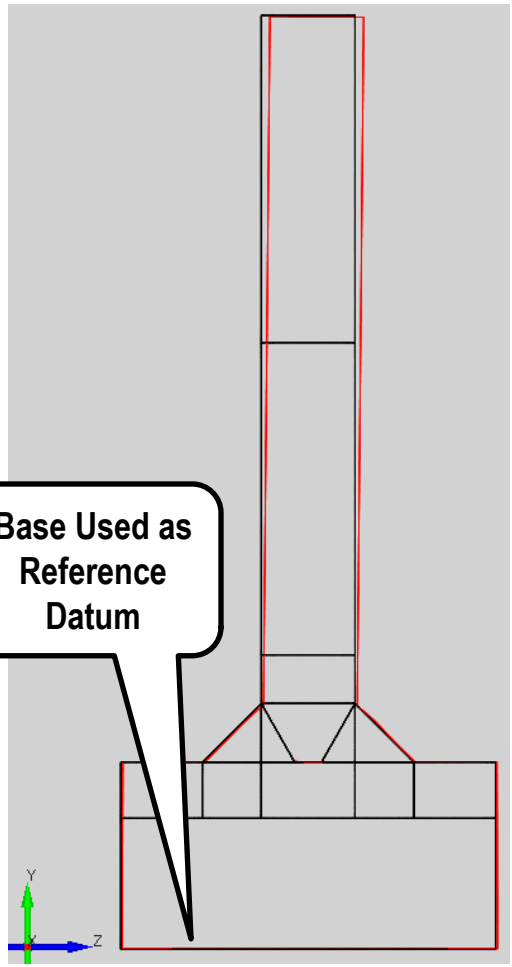


SIDE 1, Pass 1/5/6



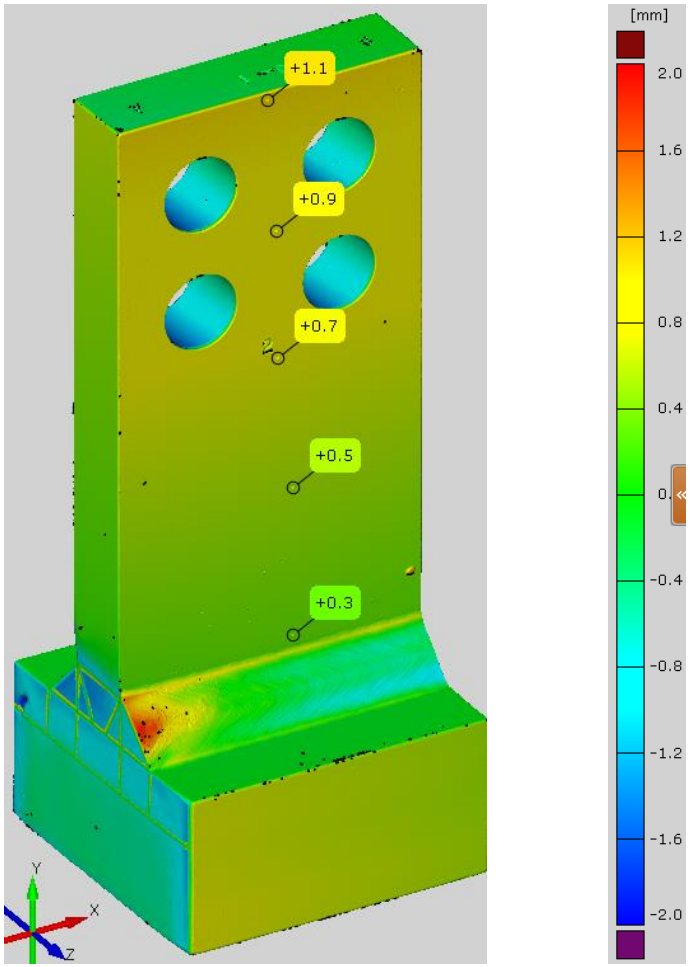
SIDE 1
Pass 1/5/6

SIDE 2
Pass 2/3/4

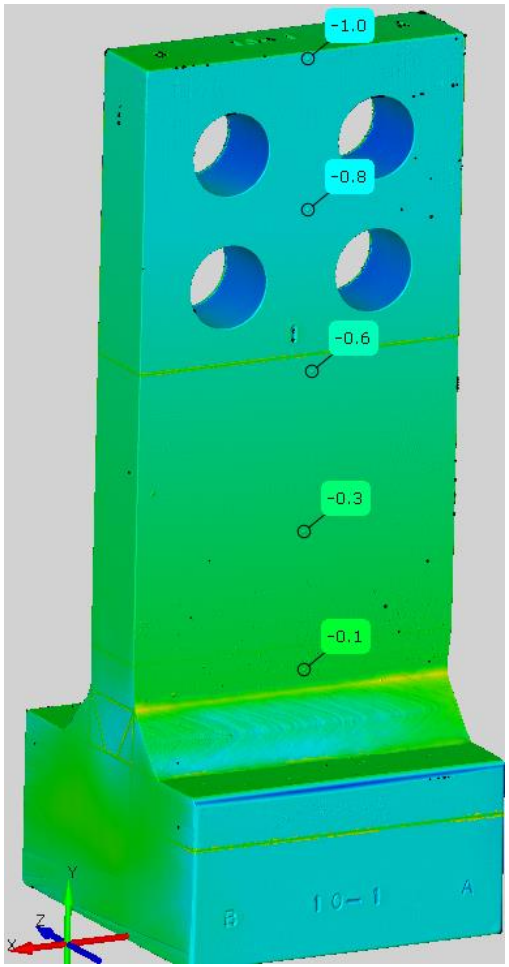


Sample 10-1 Distortion (mm)

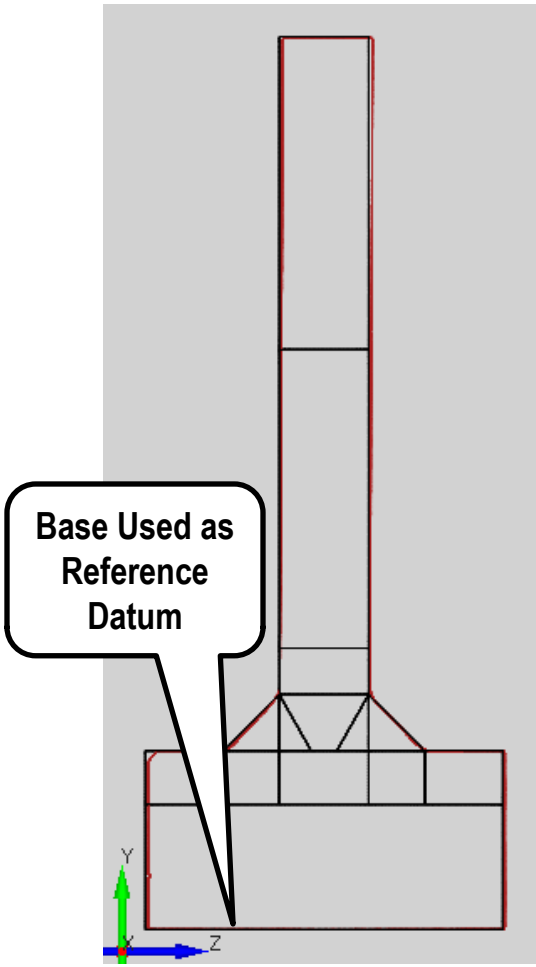
SIDE 2, Pass 2/3/4



SIDE 1, Pass 1/5/6

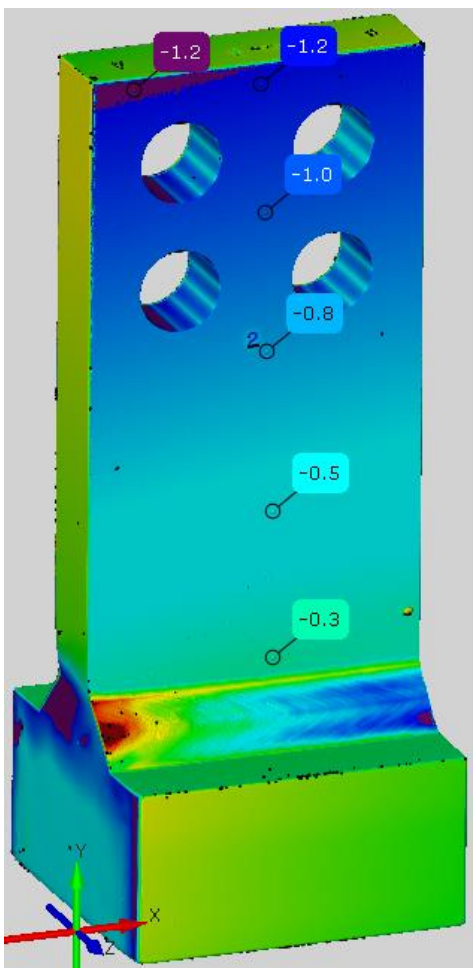


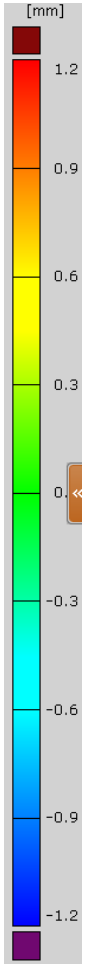
SIDE 1 Pass 1/5/6 SIDE 2 Pass 2/3/4



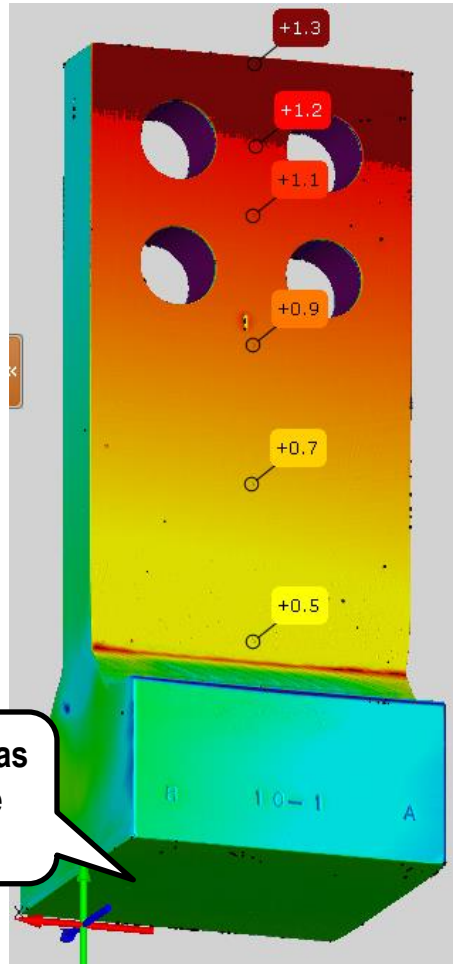
Sample (10-1) Vs. Simulation III Distortion Delta (mm)

SIDE 2, Pass 2/3/4





SIDE 1, Pass 1/5/6

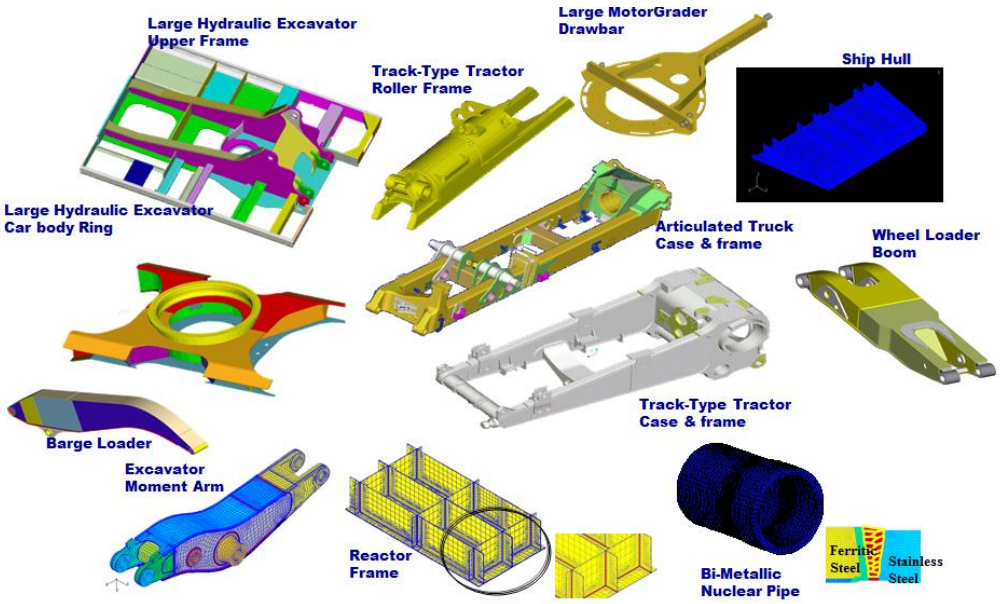


Conclusions

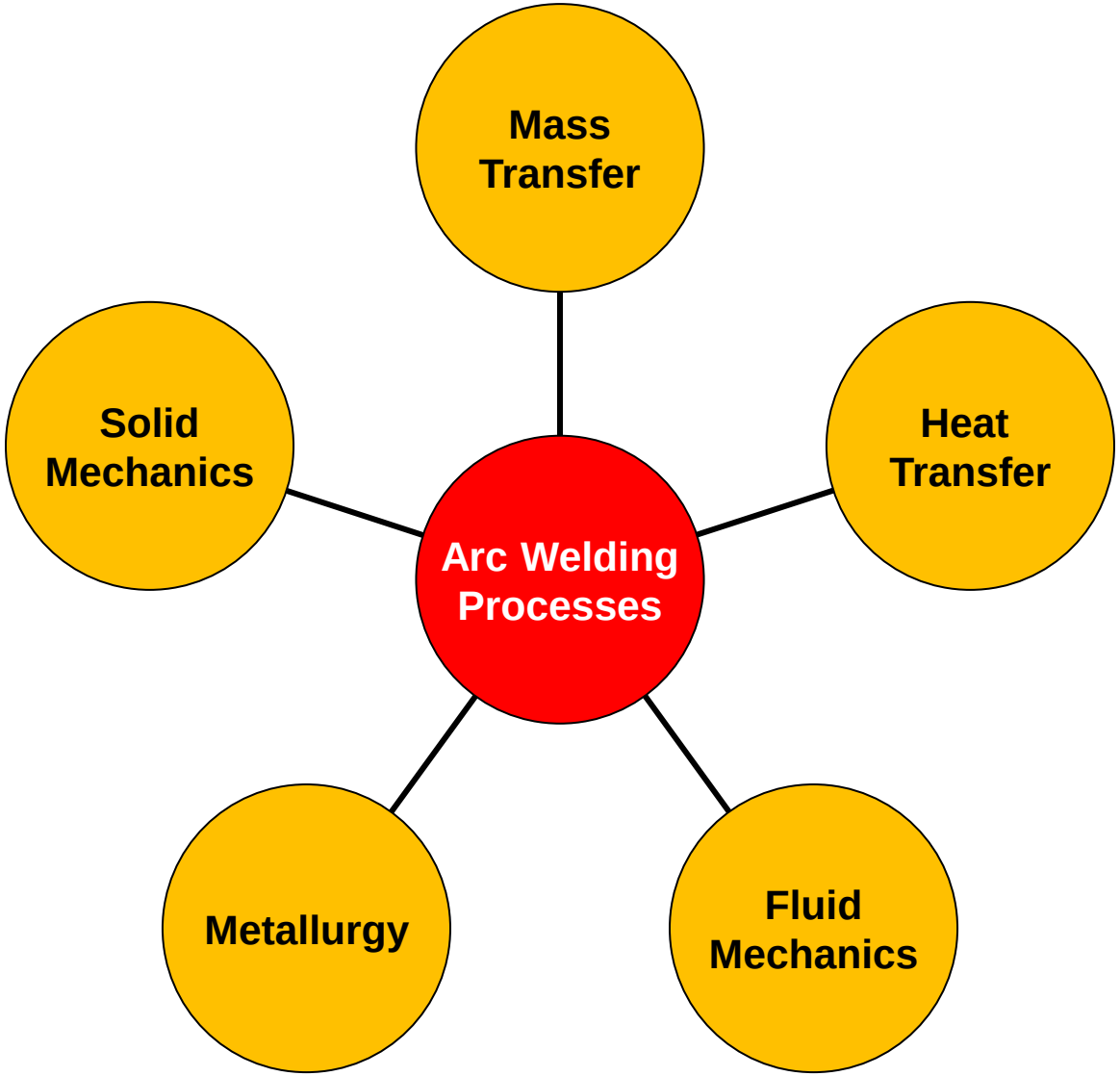
- Material Property Effect (Original Vs. World Trade Center Data)
  - Similar overall trend
  - Residual stress magnitude at the end varied ~100MPa, less change in middle
- Cooling Time Effect (Average Arc Off Time Vs. Arc Off+On Time)
  - Similar overall trend
  - Residual stress magnitude did not change with cooling times used
  - Cooling time effects can be significant, depends on the time magnitude
- Final 2015 Residual Stress at 2.5mm
  - Similar trend to prior 2013 XRD measurements (likely also off toe)
  - Compressive magnitude good
  - Tensile magnitude high
- Final 2015 Distortion
  - Similar overall trend, 50% difference on maximum distortion value
    - Aspect ratio of reference plane (part bottom) to height not ideal
    - **1mm** extra deflection at the top tip represents **0.2 deg** error in establishing the base plane.
    - Variation in tacking, fixture, plate parallelism or flatness, etc could effect scan measurements

Simulation: Overview

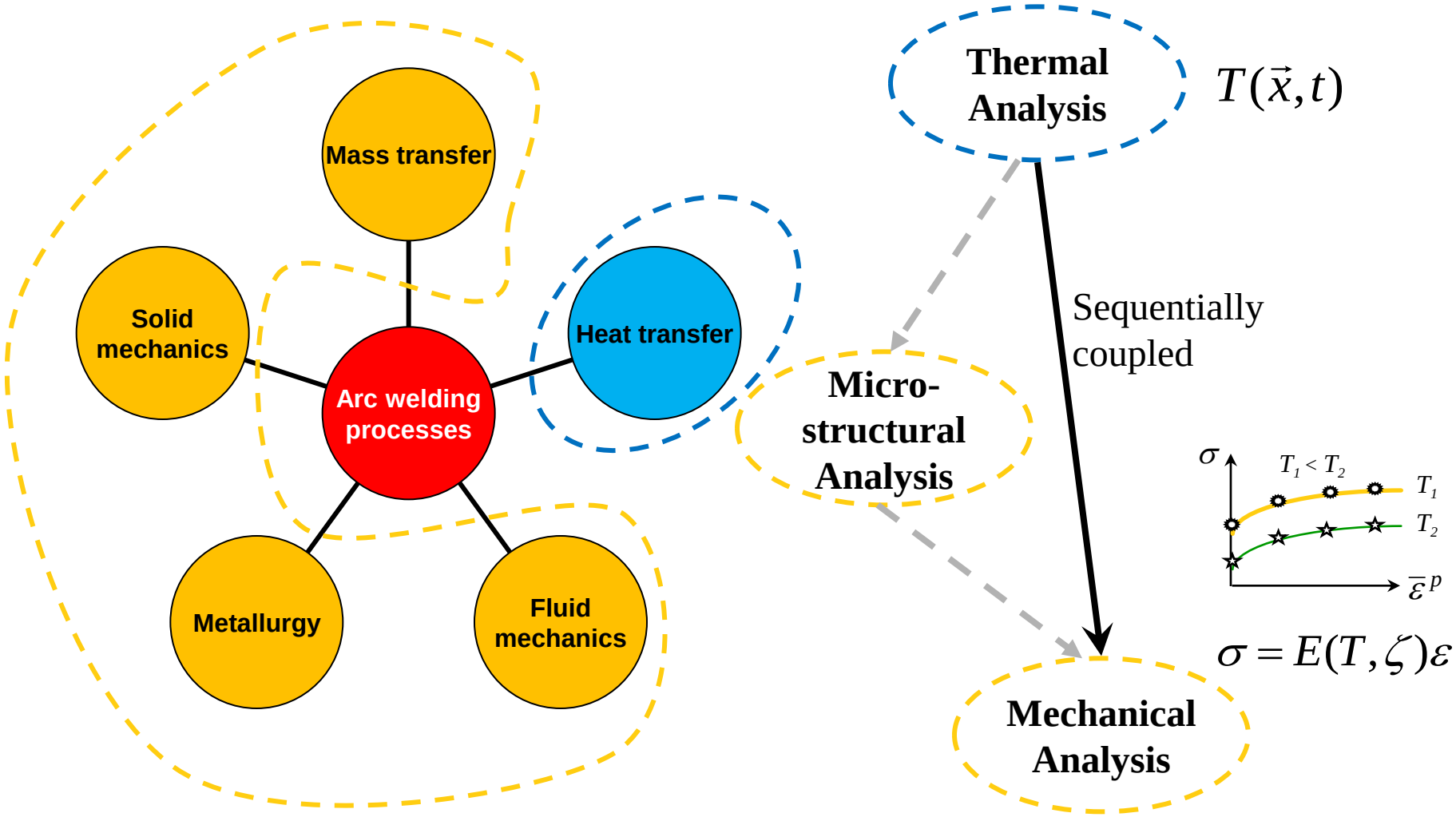
- Caterpillar Tool, VFT®
- Virtual Fabrication Technology
- Developed with
  - Battelle Memorial Institute
  - Engineering Mechanics Corporation (EMC2)
- Caterpillar & EMC2 Co-owned



Simulation: Physics & Material Behavior

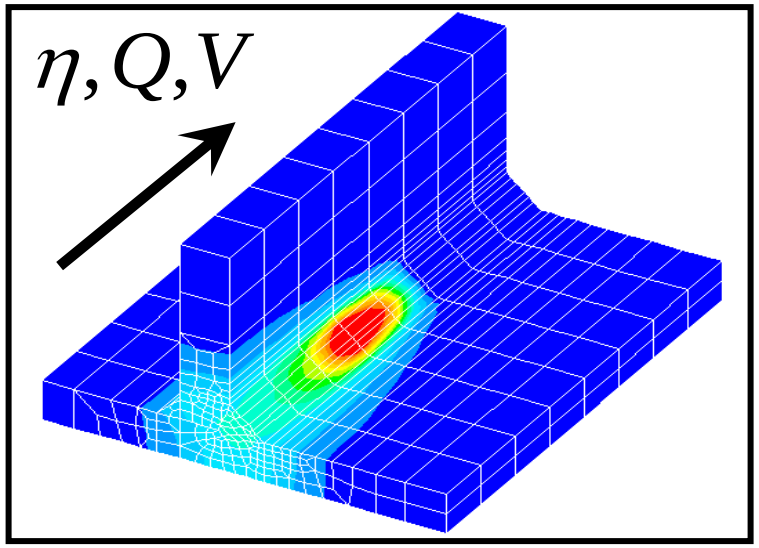


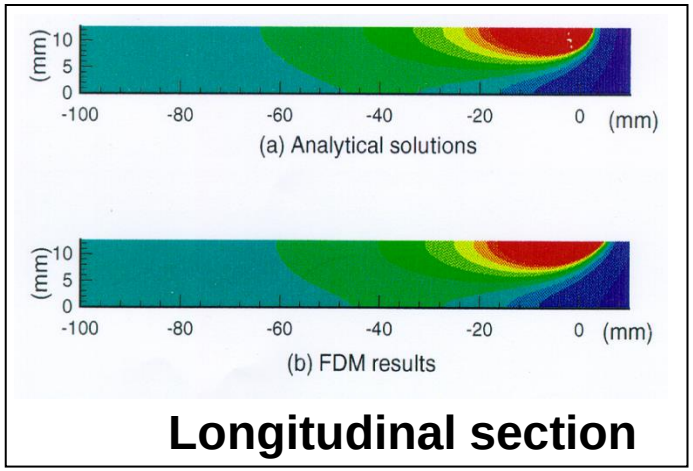
Simulation: VFT Approach



Simulation: Thermal Detail

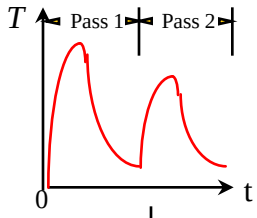
- Analytical Solution
  - Point heat source traveling in semi-infinite body (Rosenthal, 1941)
  - \+ Computationally efficient
  - – Inflexible heat source
- Numerical Solution
  - Ellipsoid heat source, *DFLUX
  - \+ Flexible heat source
  - – Less computationally efficient

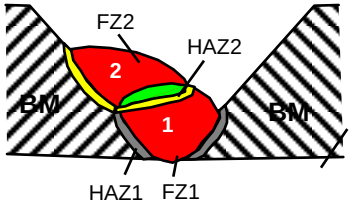




Longitudinal section

Simulation: Structural Detail





Heat Transfer

Metallurgy

Temperature History

Microstructure

Melting/Re-melting Mechanism

Phase Transformation Mechanism

Fluid Mechanics

Yield Surface

State Variable Approach

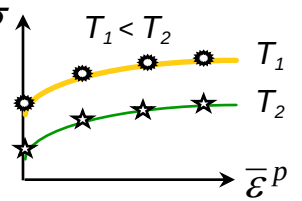
$$\Delta\varepsilon_{ij}^{Tot} = \Delta\varepsilon_{ij}^{e} + \Delta\varepsilon_{ij}^{p} + \Delta\varepsilon_{ij}^{T} + \Delta\varepsilon_{ij}^{A} + \Delta\varepsilon_{ij}^{Tr}$$

$$F(\sigma_{ij}, \alpha_{ij}, T, \Delta T, H', \bar{\varepsilon}^{p}) = 0$$

Determine: $\Delta\varepsilon_{ij}^{e}, \Delta\varepsilon_{ij}^{p}, \Delta\varepsilon_{ij}^{T}, \sigma_{ij}, \Delta\bar{\varepsilon}^{p}, \bar{\varepsilon}^{p}$

$\Delta\alpha_{ij}, \dfrac{\partial\Delta\sigma_{ij}}{\partial\Delta\varepsilon_{kl}}$ (Jacobian)

Material Data



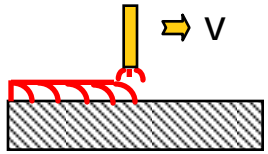
Large Deformation Mechanism

Strain Hardening Mechanism

Solid Mechanics

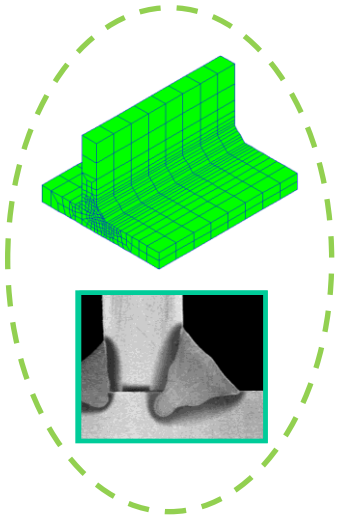
Mass Transfer

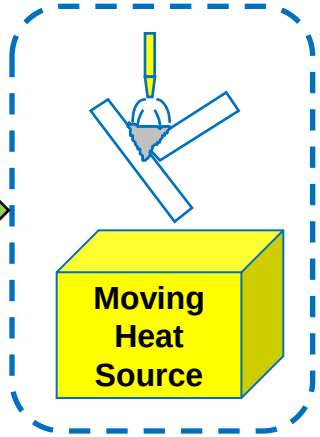
Virtual Elements Mechanism



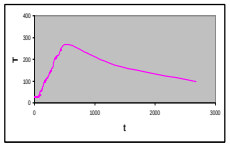
Simulation: VFT Approach

- Apply welding heat input
- Calculate thermal history
- Apply *thermal* loads
- Boundary conditions, set by fixture





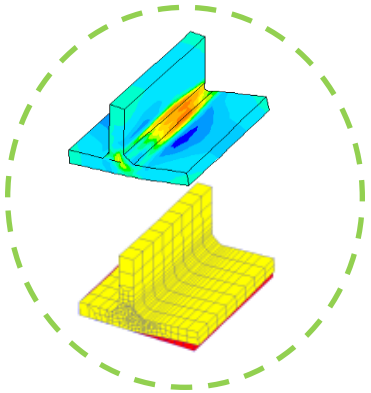
Thermal Analysis in VFT®

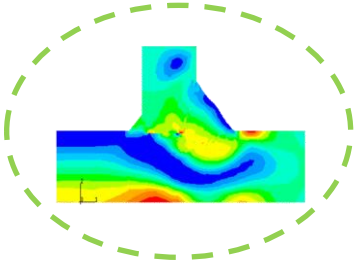


UFIELD

Structural Analysis in ABAQUS®

Distortion





Residual stress

Alternate X-Ray Diffraction Opportunities

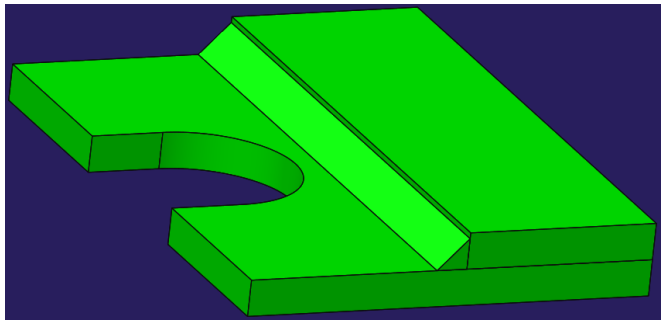
Lab Source

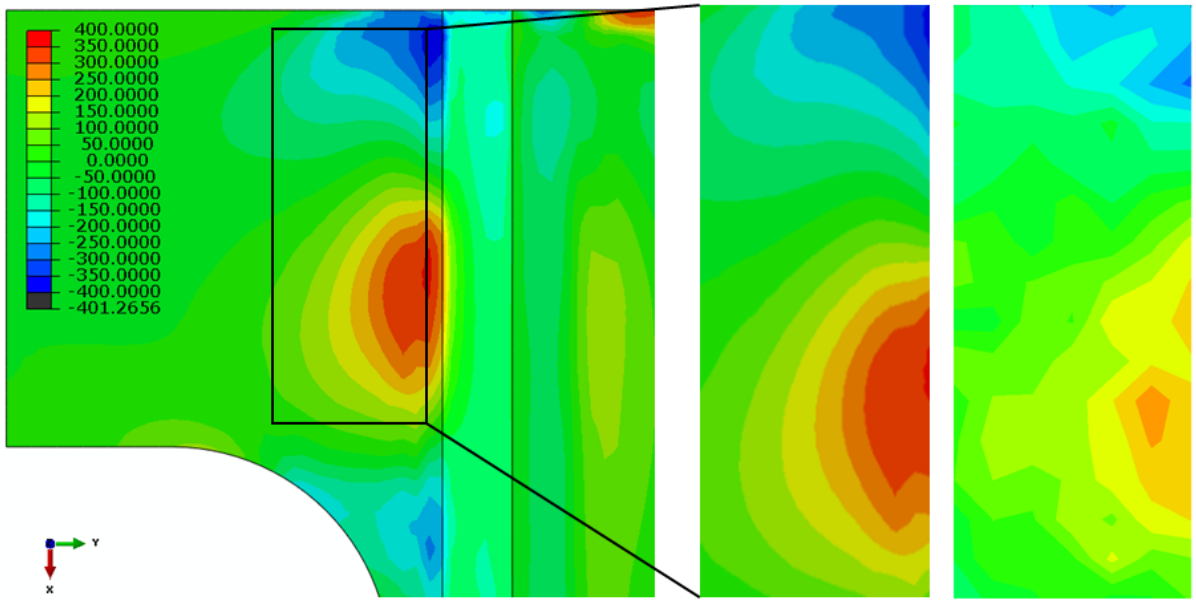
- Lambda, Universities, etc
- Pro
  - Availability
  - Cost
  - Portable, fewer sample size limitations
- Con
  - Point data capture
  - Limited depth penetration
  - Reflection only

High Energy Source

- APS, Argonne National Lab; CHESS, Cornell University
- Pro
  - Area data capture
  - Better depth penetration
  - Reflection & Transmission
- Con
  - Availability
  - Cost ($0 if publishable)
  - Sample size limitations

Alternate X-Ray Diffraction Opportunities





Model Model EDD Measurement

QUESTIONS?

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