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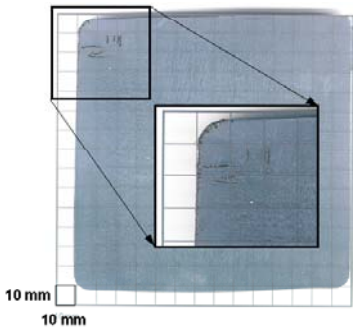
Stress and Hot Tearing of Solidifying Steel Shells: Experiment and Simulation

Matthew Rowan
(Ph. D. Student)

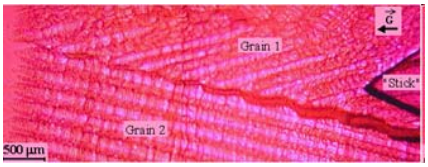
Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign

Background

- Stress develops in solidifying shell due to:
  - 1) Thermal loading
  - 2) Mechanical loading
- Phenomena:
  - Thermal contraction
  - Phase transformation
  - Temperature gradients
  - Interface friction
- Leads to Cracks
  - Internal hot tears
  - Surface cracks



Bernhard C.:*Anforderungen an prozessorientierte Heißrissbildungsmodelle* BHM, Vol. 149 (2004), 90-95.



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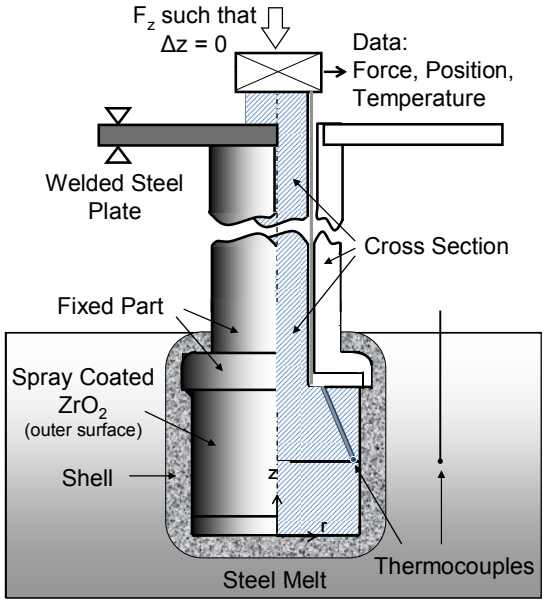
Objectives

1) Develop a thermo-mechanical model of the Submerged Split Chill Contraction (SSCC) test

2) Predict temperature measurements, shell growth history and reaction forces

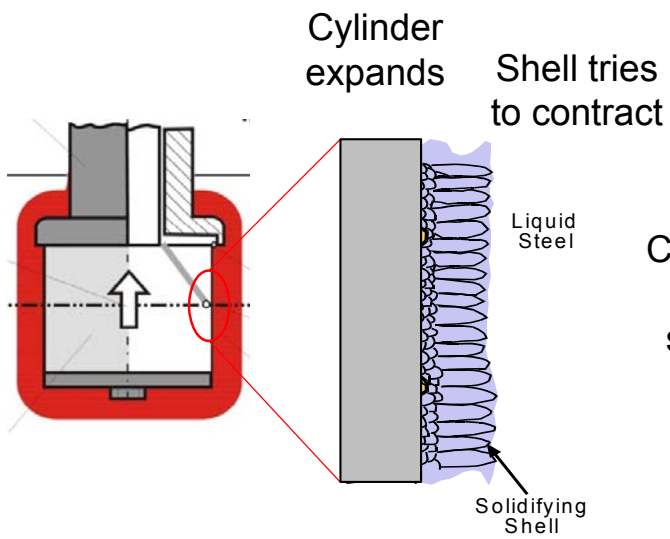
3) Combine experiments and models to enhance understanding of the mechanical behavior of steel during initial solidification and hot tearing

SSCC Experimental Apparatus



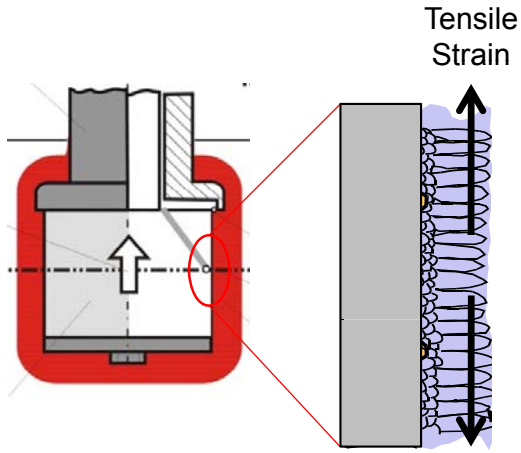
Pierer R., Bernhard C., *High Temperature Behavior during Solidification of Peritectic Steels under Continuous Casting Condiitions*, Materials Science & Technology (MS&T '06), Conference and Exihibition, Cincinnati, USA, October 2006

Hot Tear Formation in SSCC



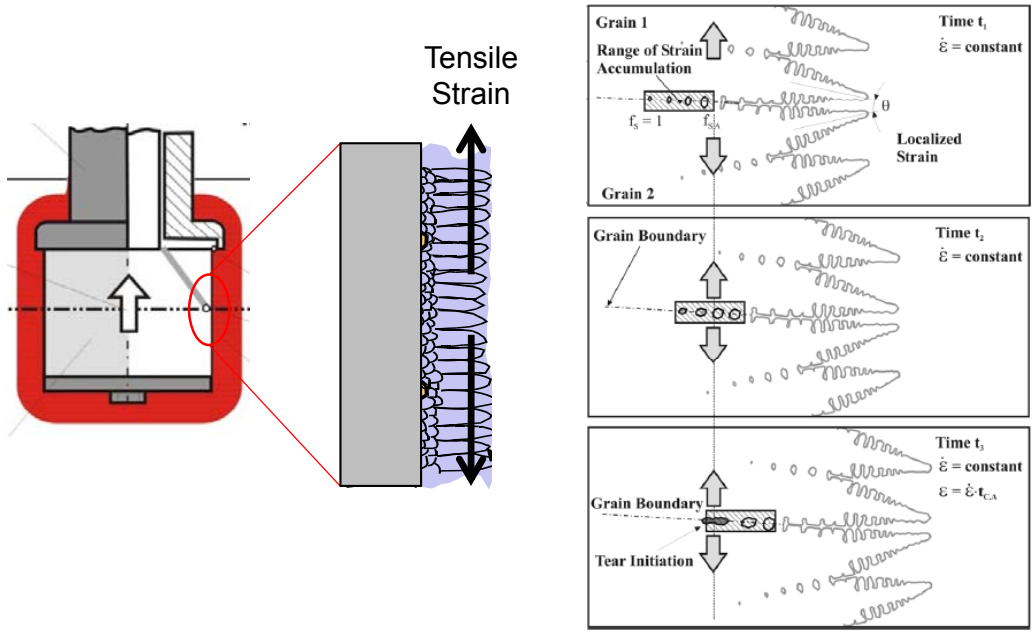
Cylinder prevents contraction of solidifying shell

Hot Tear Formation in SSCC



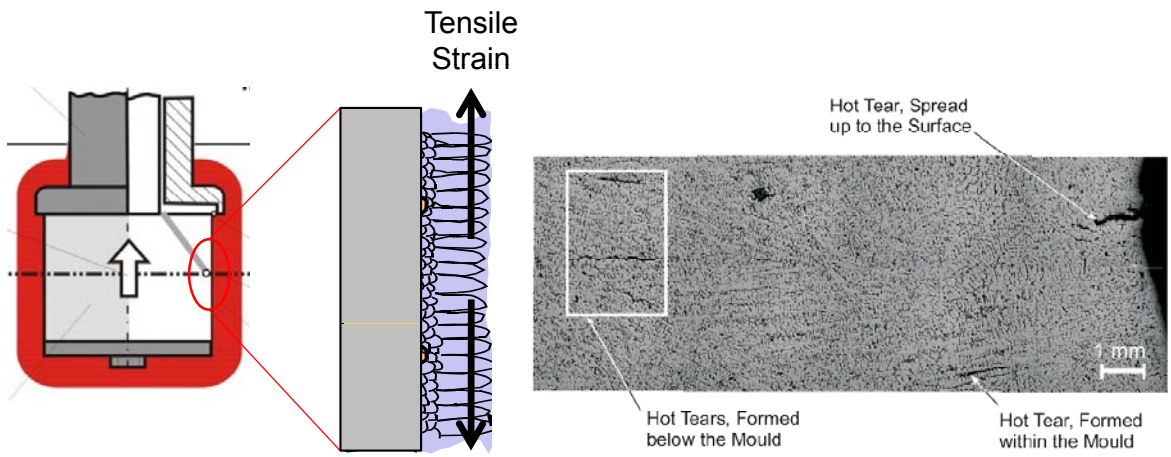
Tensile strains develop perpendicular to dendrite growth direction

Hot Tear Formation in SSCC



Pierer R., Michelic S., Bernhard C. *A Hot Tearing Criterion for the Continuous Casting Process,* Private Communication.

Hot Tear Formation in SSCC



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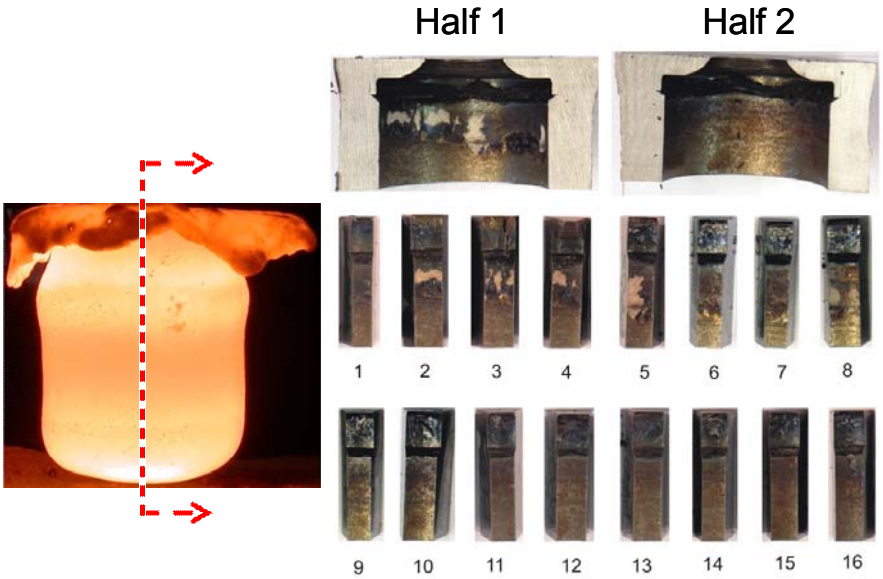
SSCC Test

Final Shell Shape

Removed Solidified Shell



Experimental Data

- Experiments performed at University of Leoben
- Thermocouple measurements
  - 2 locations in the test cylinder
  - 2 locations in the steel melt
- Contraction Force
- Shell Thickness
- Alloying effect important
  - C, Si, Mn, P, S, Ni

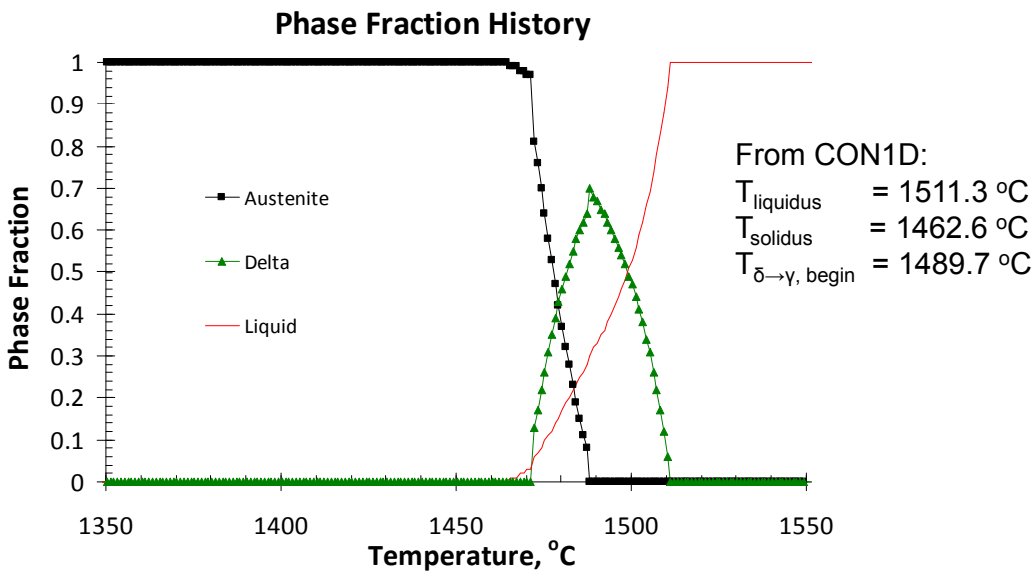
Thermo-mechanical Modeling

- Solve 2-D axisymmetric transient heat conduction and elastic-viscoplastic stress equation
- Temperature and phase-dependent
  - thermal conductivity
  - specific heat
  - coefficient of thermal expansion
  - elastic modulus
- Implement Kozlowski III and modified power law constitutive relations into ABAQUS using Koric UMAT routine*

* Koric, S, Thomas, B. G., "Efficient thermo-mechanical model for solidification processes", *International Journal for Numerical Methods in Engineering, Vol. 66 (12), 2006, pp. 1955-1989.*

Phase Fraction – PP05 Case

%C	%Mn	%S	%P	%Si	%Al	%Fe
0.315	1.44	0.0051	0.0039	0.356	0.0715	Balance



Steel Property Equations

Temperature-dependent properties: k and H [Pehlke,1982], E [Mizukami,1977], α_t [Pehlke,1982, Harste,1988 for solid, Cramb, 1993 for liquid].

Elastic-viscoplastic model for Austenite (Kozlowski)

$$\dot{\varepsilon}(1/\sec.) = f(\%C)\left[\sigma(MPa) - f_1\left(T\left(^oK\right)\right)\varepsilon\left|\varepsilon\right|^{f_2\left(T\left(^oK\right)\right)-1}\right]^{f_3\left(T\left(^oK\right)\right)} \exp\left(-4.465\times10^4\left(^oK\right)/T\left(^oK\right)\right)$$

$$f_1\left(T\left(^oK\right)\right) = 130.5 - 5.128\times10^{-3}T\left(^oK\right)$$

$$f_2\left(T\left(^oK\right)\right) = -0.6289 + 1.114\times10^{-3}T\left(^oK\right)$$

$$f_3\left(T\left(^oK\right)\right) = 8.132 - 1.54\times10^{-3}T\left(^oK\right)$$

$$f(\%C) = 4.655\times10^4 + 7.14\times10^4\%C + 1.2\times10^5(\%C)^2$$

Modified Power Law Model for δ-ferrite (Zhu)

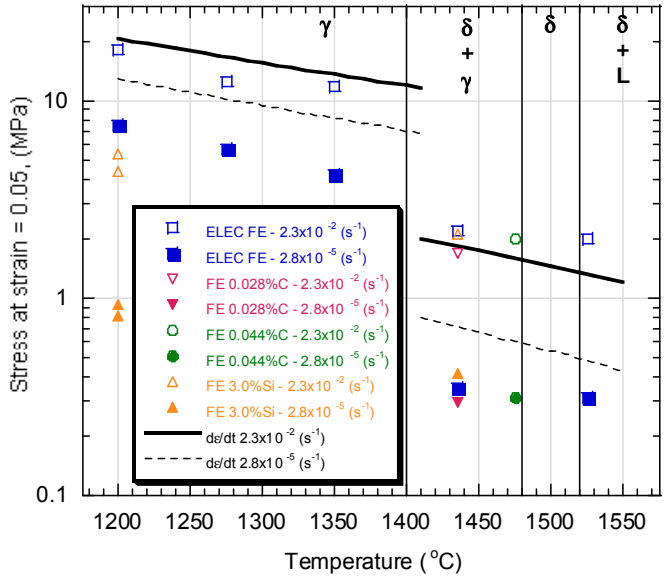
$$\dot{\varepsilon}(1/\sec.) = 0.1\left|\sigma(MPa)\Big/ f(\%C)\left(T\left(^oK\right)/300\right)^{-5.52}(1+1000\varepsilon)^m\right|^n$$

$$f(\%C) = 1.3678\times10^4(\%C)^{-5.56\times10^{-2}}$$

$$m = -9.4156\times10^{-5}T\left(^oK\right) + 0.3495$$

$$n = 1\Big/1.617\times10^{-4}T\left(^oK\right) - 0.06166$$

Constitutive Behavior of Steel - Tension



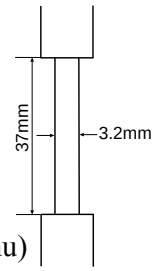
- *Lines:*

  Constitutive Model Predictions

- *Symbols:*

  *Wray measurements**

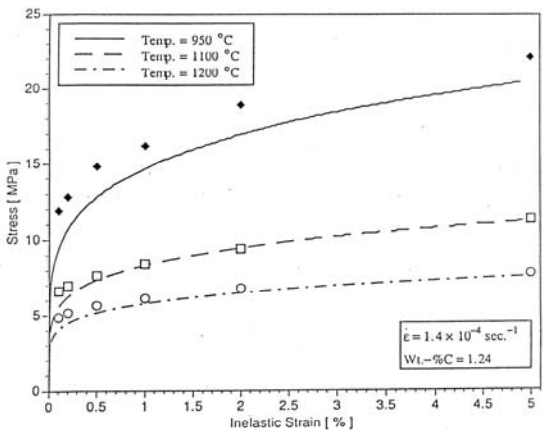
* P. J. Wray, *Met. Trans, A,* V7A, 1976, P1621-1627

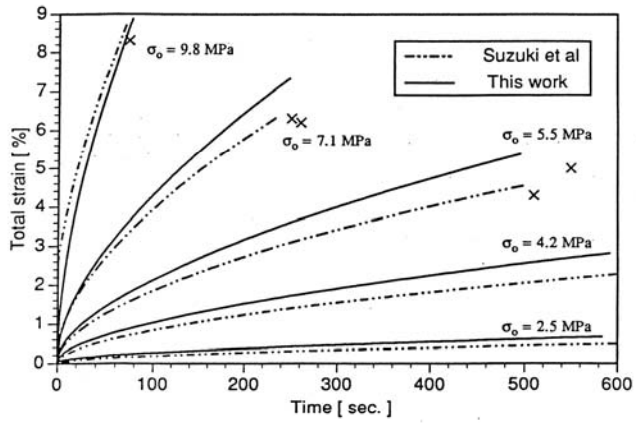


Model Implementation: If >10% delta-ferrite: delta-ferrite model (Zhu)

If <10% delta-ferrite: austenite (Kozlowski)

Constitutive Behavior of Steel - Creep





*Kozlowski, P et al, "Simple Constitutive Equations for Steel at High Temperature", *Met. Trans. A,* Vol. 23A, 1992, pp. 903-918.

Model Validation

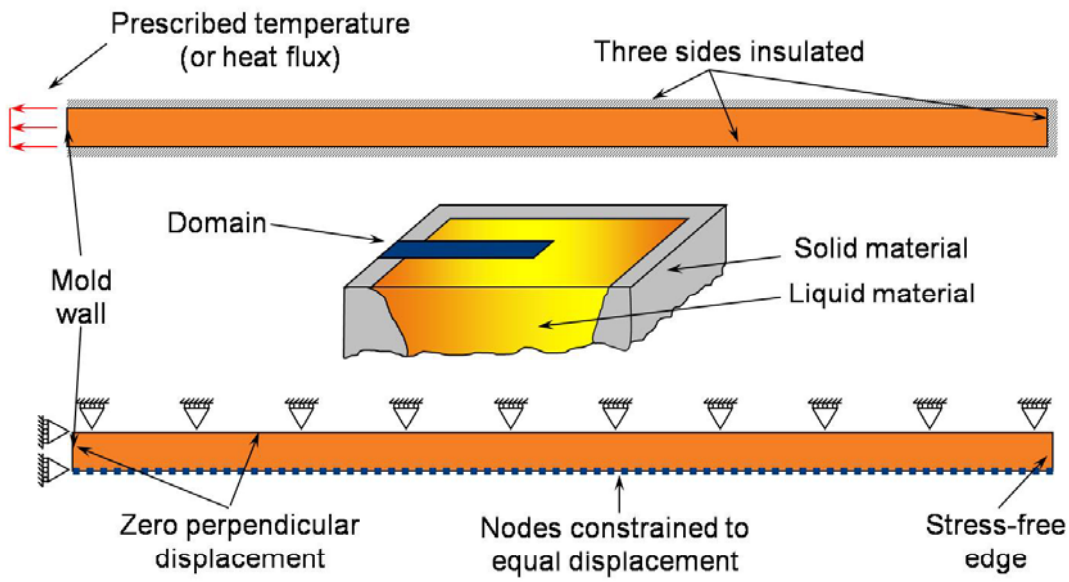
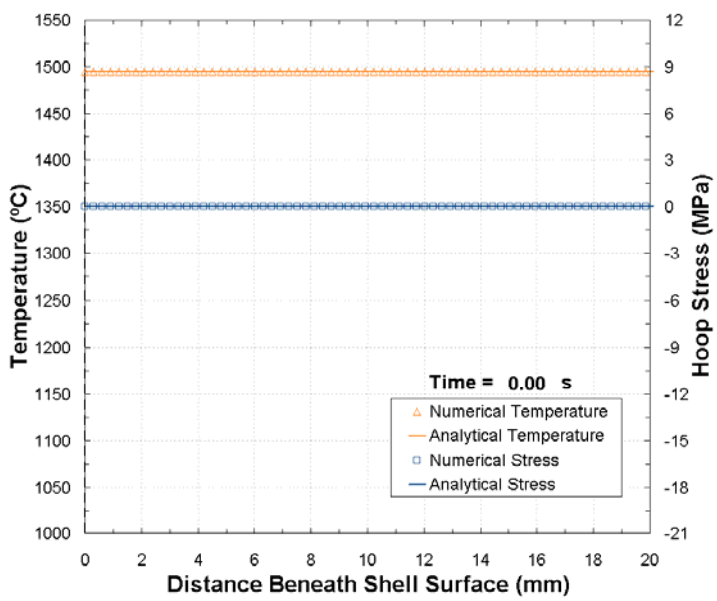


Image courtesy of L. Hibbeler

Comparison with Analytical Solution

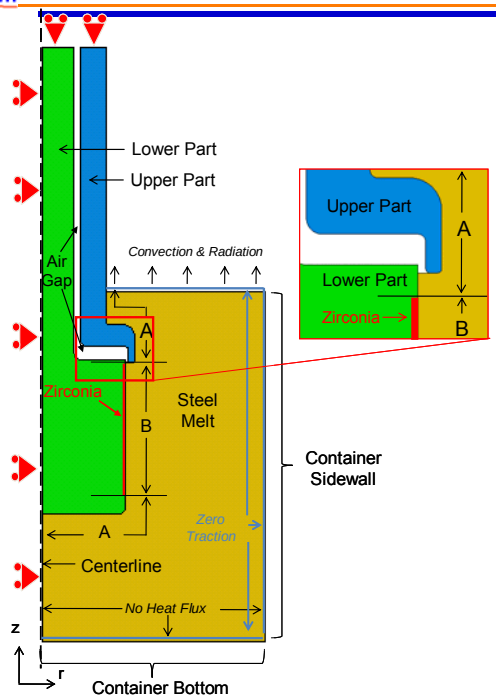
Property/Condition	Value
Density	7500.0 kg/m³
Specific heat	661.0 J/(kg·K)
Latent heat	272.0 kJ/kg
Thermal conductivity	33.0 W/(m·K)
Thermal expansion coefficient	20.0E-6 m/(m·ºC)
Poisson's ratio	0.3 –
Initial temperature	1495.0 ºC
Liquidus temperature	1494.48 ºC
Solidus temperature	1494.38 ºC
Mold temperature	1000.0 ºC
Yield stress at mold temp.	20.0 MPa
Yield stress in liquid material	35.0 kPa
Elastic modulus in solid	40.0 GPa
Elastic modulus in liquid	14.0 GPa

Courtesy of L. Hibbeler



J.H. Weiner and B.A. Boley, "Elasto-Plastic Thermal Stresses in a Solidifying Body." *Journal of the Mechanics and Physics of Solids*, 11 (1963), No. 3. pg 145-154.

Boundary Conditions

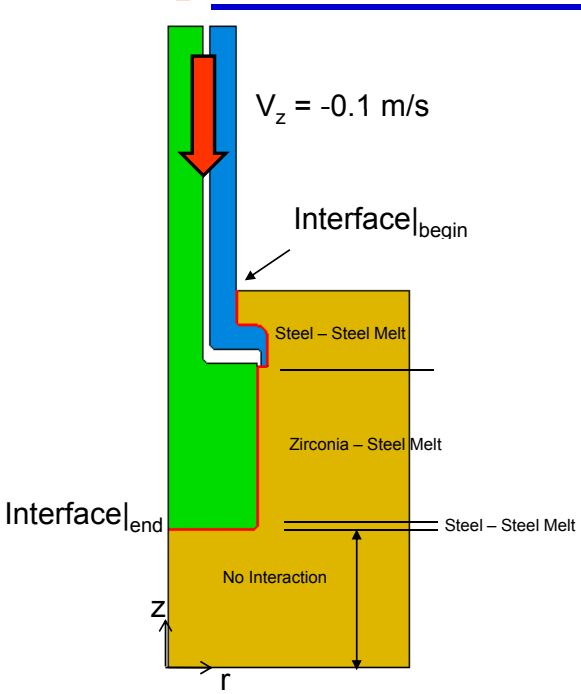


4-node axisymmetric elements

$T_{initial,\ steel\ melt}$ ~1540 °C

$T_{initial,\ test\ cylinder}$ =25 °C

Boundary Conditions - Interaction

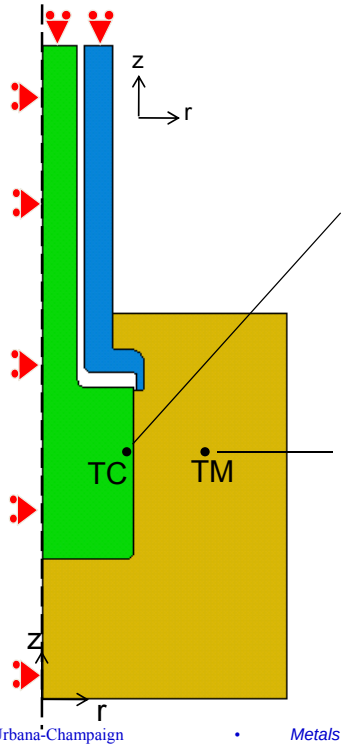


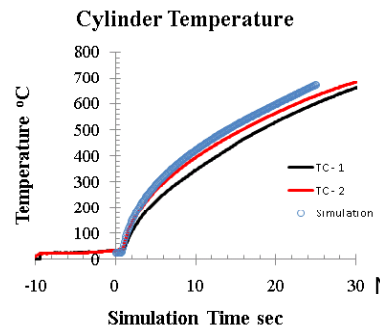
$$\mathrm{HTC}\left(\frac{W}{m^2K}\right)=\begin{cases}0, & 0.040\ \mathrm{m} > V_z\cdot t > 0\\ 1850, & 0.047\ \mathrm{m} \ge V_z\cdot t \ge 0.040\ \mathrm{m}\\ 2500, & 0.088\ \mathrm{m} > V_z\cdot t > 0.047\ \mathrm{m}\\ 1850, & 0.110\ \mathrm{m} \ge V_z\cdot t \ge 0.088\ \mathrm{m}\\ 0, & V_z\cdot t > 0.110\end{cases}$$

The interface is treated in a Lagrangian frame of reference.

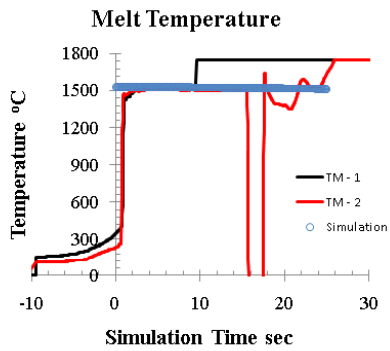
The conditions on the HTC determine the thermal interaction between the two surfaces.

Temperature History – PP05

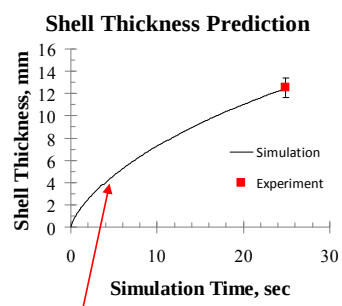


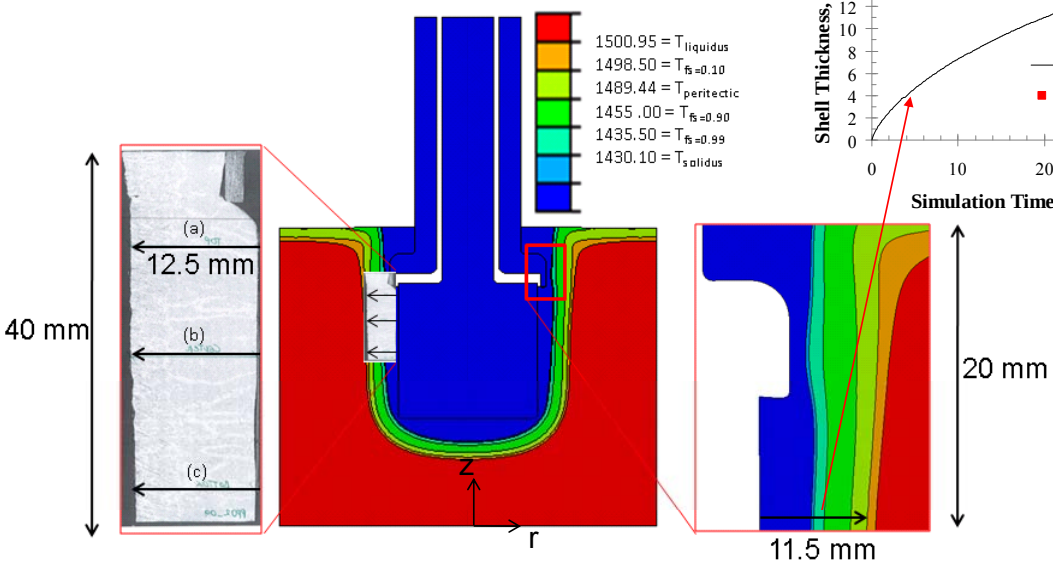


Note short delay in $T_{increase}$ (immersion).

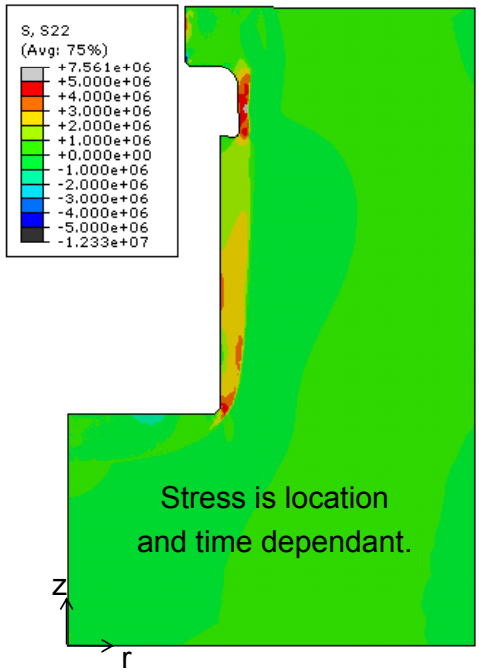


Shell Growth Profile

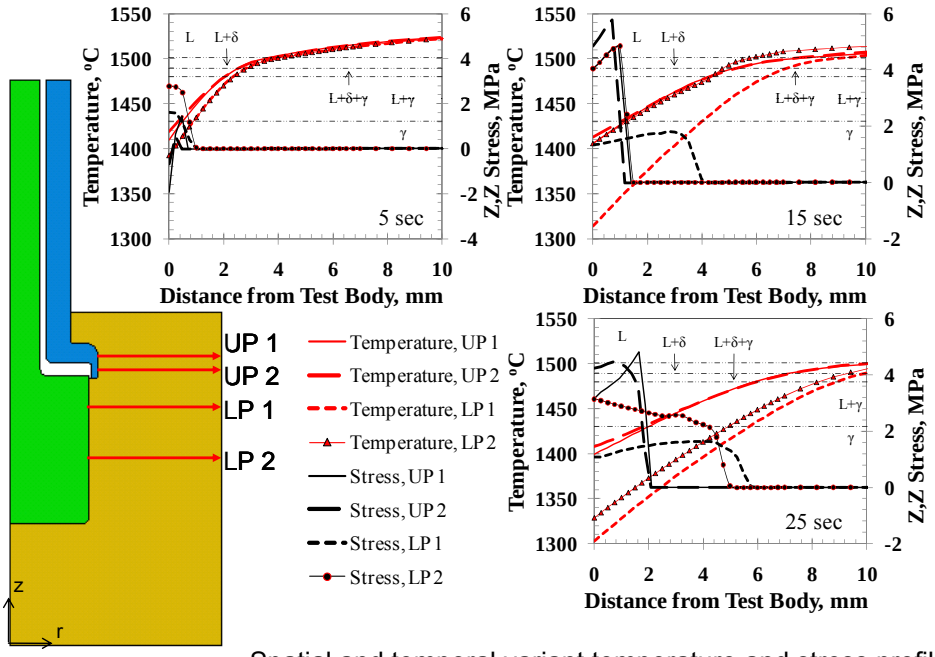




Stress Perpendicular to Shell Growth Direction, 25 sec

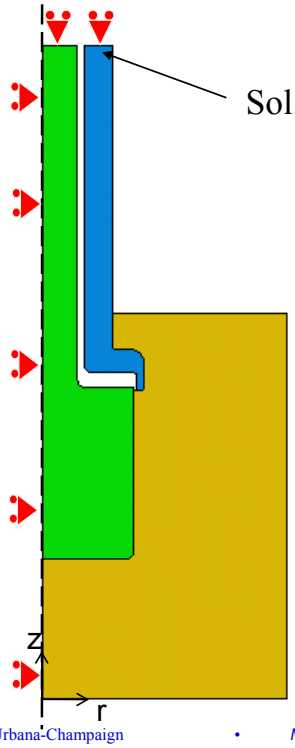


Phase Dependant Shell Strength

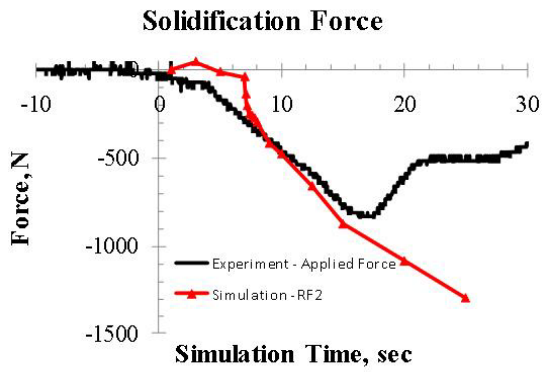


Spatial and temporal variant temperature and stress profile.

Solidification Force

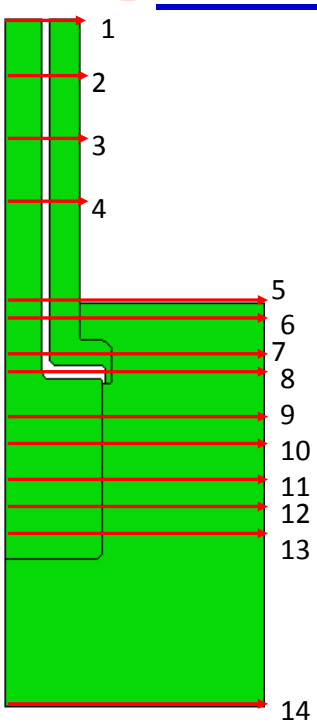


$$\text{Sol. Force} = \sum_{i=1}^{\#\,\text{nodes}} (\text{Reaction Force})_i$$



This is a single value from a shell solidifying at a complex 3D interface.

So How Is the Force Determined?



At t = 10 sec, $F_{measure}$ = - 476 N

Location	Lower Part	Upper Part	Zirconia	Interface	Shell	Shell + Liquid	Liquid	Total
1	476	-476	N/A	N/A	N/A	N/A	N/A	0
4	475.9997	-476.0019	N/A	N/A	N/A	N/A	N/A	-0.0022
5	476.00	-476.63	N/A	1.28	0.00	0.12	0.00	0.77
7	476	111.53	N/A	8.05	-498.16	-85.79	-15.04	-3.41
8	476	-19.55	N/A	0	-442.35	1.35	-15.48	-0.03
9	-39825.81	N/A	40410.78	-3.42	-588.1	7.26	-10.28	-9.57
11	-71768.13	N/A	72793.15	-2.3	-1017.47	3.11	-12.68	-4.32
13	-7303.56	N/A	8416.86	3.12	-1102.38	3.52	-17.53	0.03

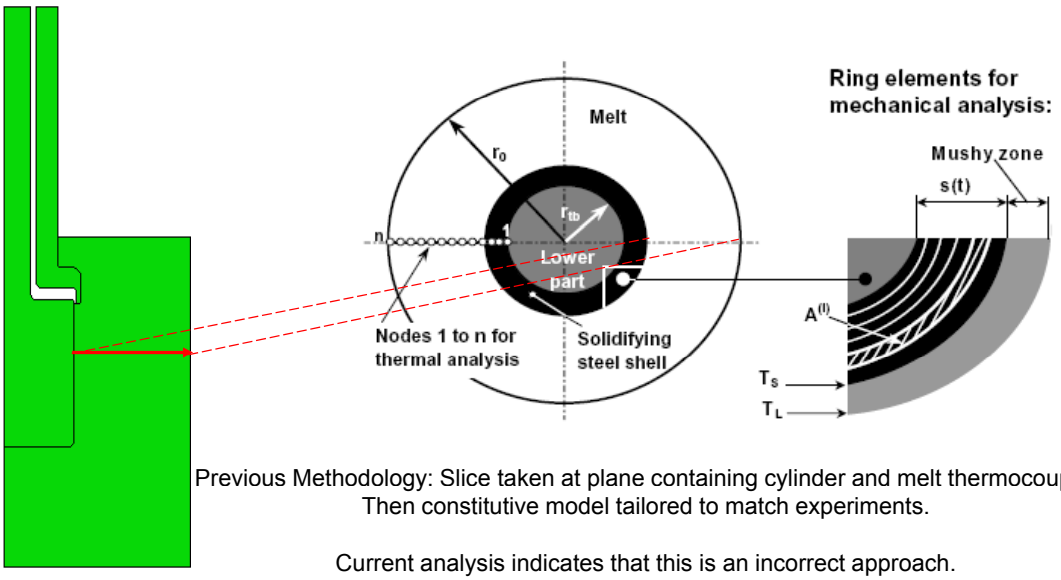
Large forces

Increasing shell force magnitude

Force ≈ 0

No Single Location Matches Measurement !

Previous Methods of Determining Force

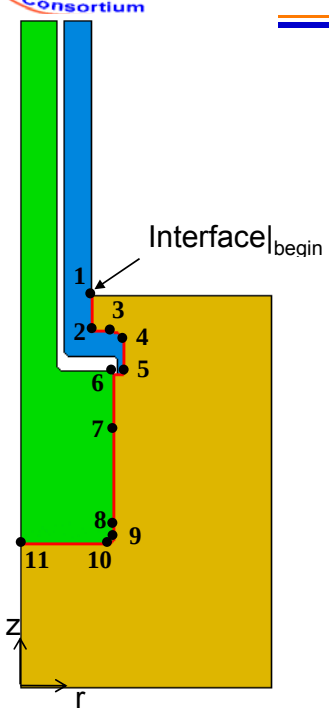


Previous Methodology: Slice taken at plane containing cylinder and melt thermocouple. Then constitutive model tailored to match experiments.

Current analysis indicates that this is an incorrect approach.

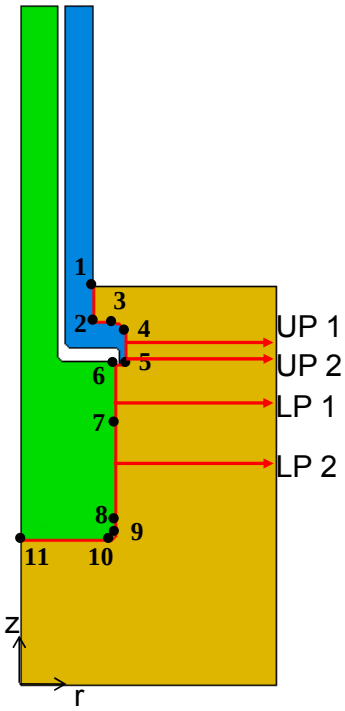
Pierer R., Bernhard C. and Chimani C. Evaluation of Common Constitutive Equations for Solidifying Steel. *BHM,* 150, 2005, pp. 163-169.

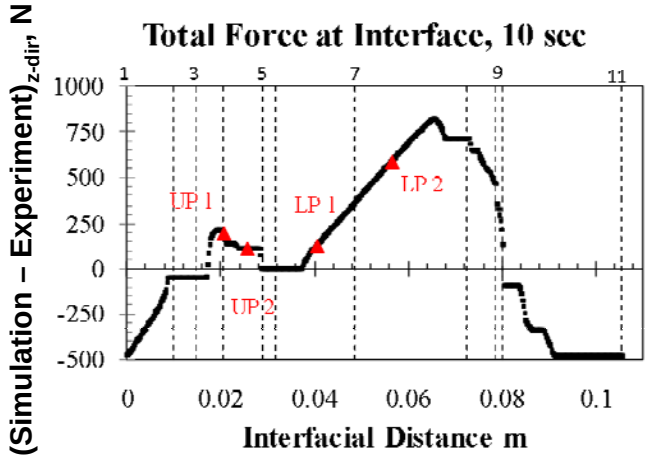
Investigation of Interfacial Forces



- Free Body Diagram: Interface
- Force at Interface = Shear + Normal Forces
  - In ABAQUS: CSHEARF2+CNORMF2
- I will plot the running sum of these two forces at each node
  - Each plotted value is the nodal + previous node values

Comparison of Interface Forces and Shell Slices

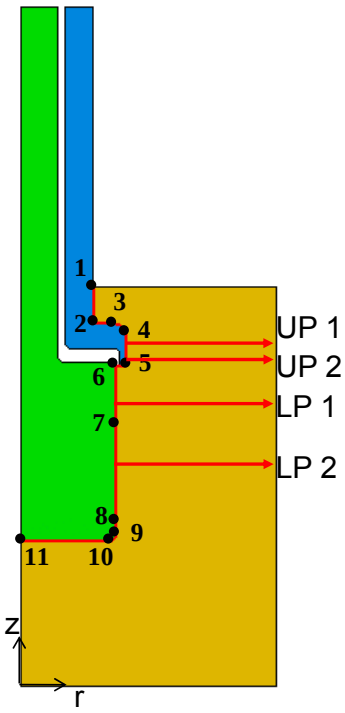


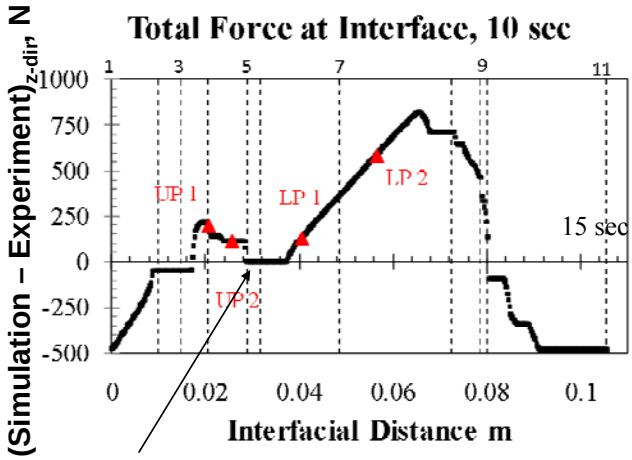


Looking for where plotted force = 0 (Simulation = Experiment)
This indicates the location that the force is actually being measured.

Forces found from slices (UP1, UP2, LP1 & LP2), match the local total interface force.

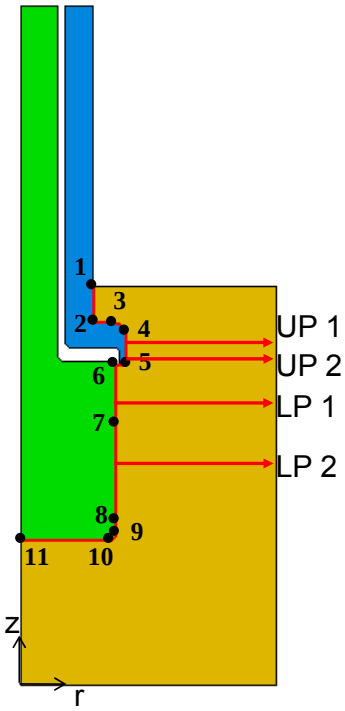
Comparison of Interface Forces and Shell Slices

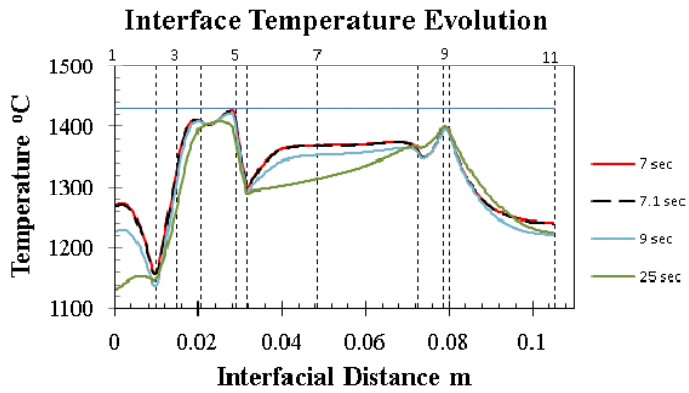




This corresponds to the shell connecting the upper and lower parts.

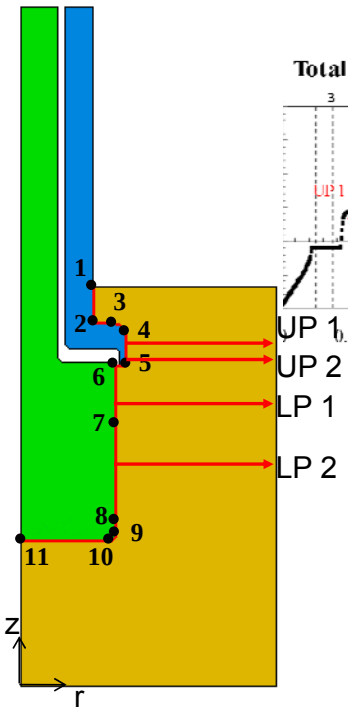
Solidification Force is Determined by Shell Interface Temperature

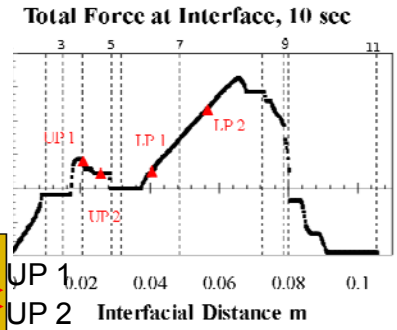


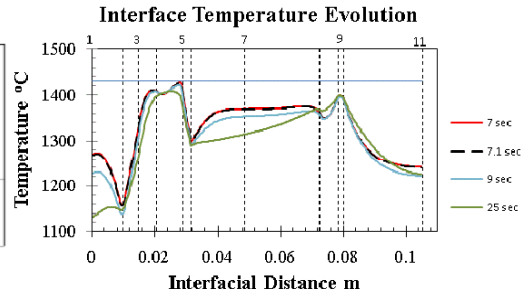


Interfacial location where SSCC test is measuring force also, coincidentally, corresponds to the region of the interface at the highest temperature.

The SSCC Measures

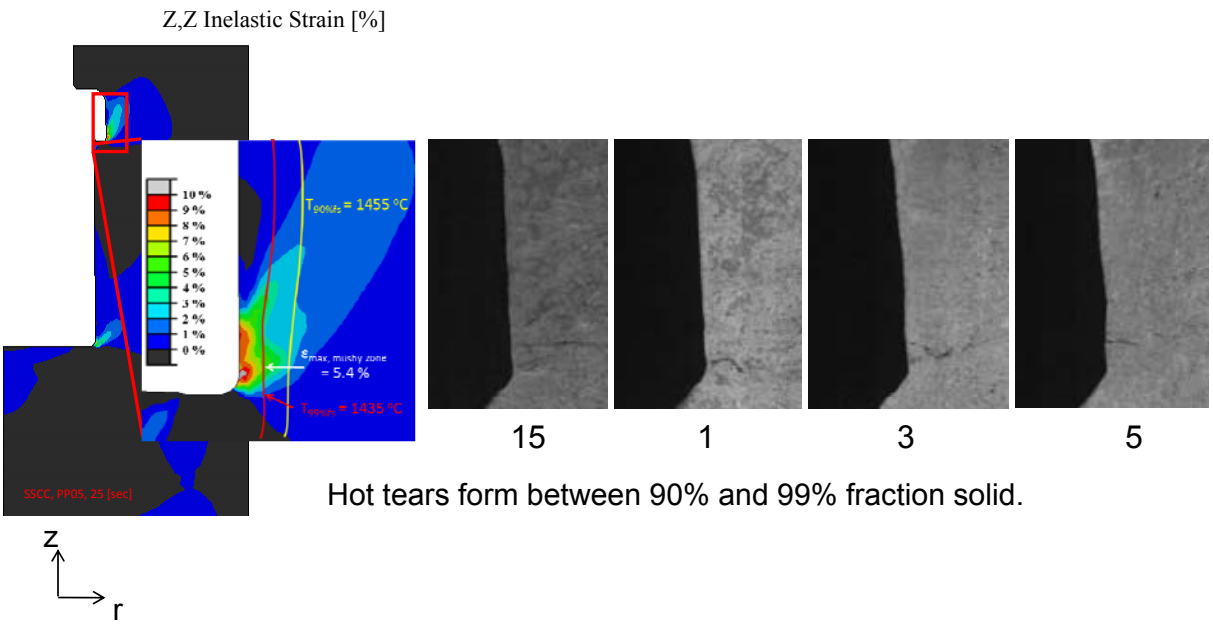






The SSCC test measures the strength of the shell at the highest interfacial temperature, which also connects the upper and lower parts!!!!

Good Comparison between Max. Strain Prediction and Observed Cracks



Hot tears form between 90% and 99% fraction solid.

Conclusions

Model capable of predicting thermo-mechanical behavior of solidifying steel for different carbon contents

Validated with measured temperature profiles

Elastic-viscoplastic constitutive model utilizing separate austenite and delta-ferrite equations appears reasonable

Conclusions

The SSCC test measures the strength of the shell at the highest interfacial temperature, which also connects the upper and lower parts.

Cracks are predicted in regions of high surface temperature where local strain concentration causes hot tears between dendrites perpendicular to the solidification direction

Acknowledgments

Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Corus, LWB Refractories, Nucor Steel, Nippon Steel, Postech, Posco, ANSYS-Fluent)

National Center for Supercomputing Applications (NCSA) at UIUC – “Tungsten” cluster

Christian Doppler Laboratory (Univ. Leoben)

Lance Hibbeler, Seid Koric