ANNUAL REPORT 2009

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

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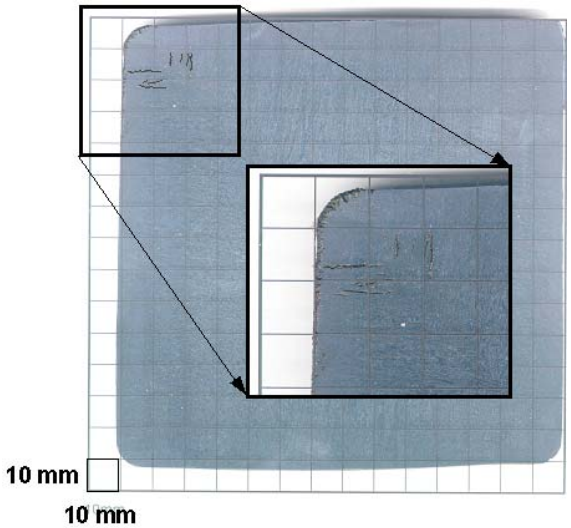
Background

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



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

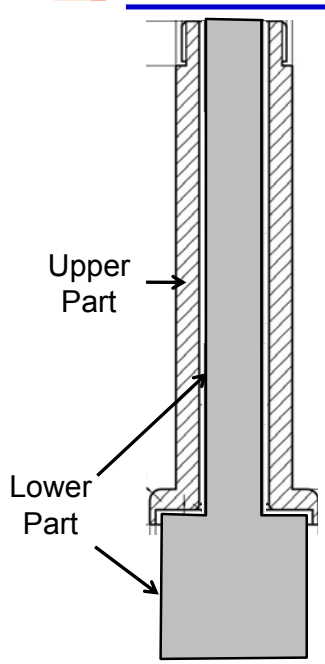
Objectives

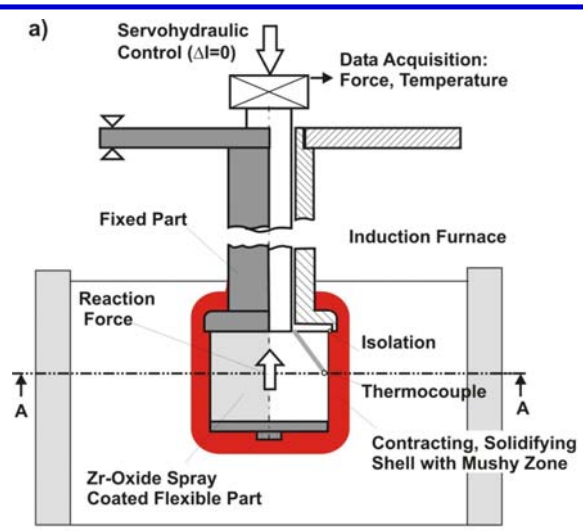
1) Develop a thermo-mechanical model of the Submerged Split Chill Contraction (SSCC) test

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

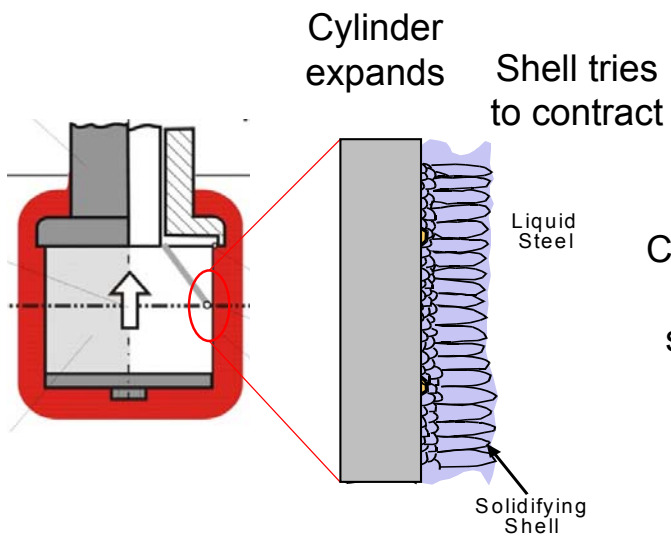
SSCC Experimental Apparatus





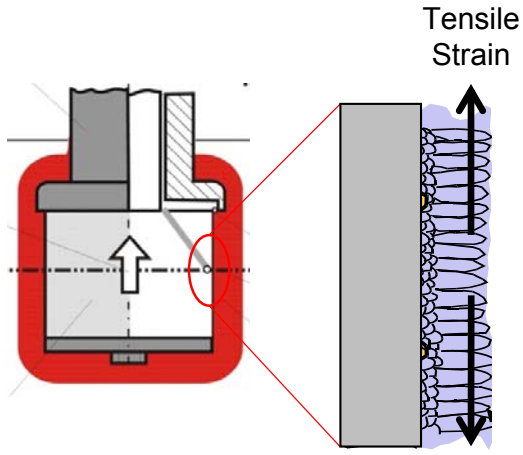
Pierer R., Bernhard C., *High Temperature Behavior during Solidification of Peritectic Steels under Continuous Casting Condiitions*, Materials Science & Technology (MS&T '06), Conference and Exihibition, Cincinnati, USA, October 2006

SSCC Experimental Apparatus



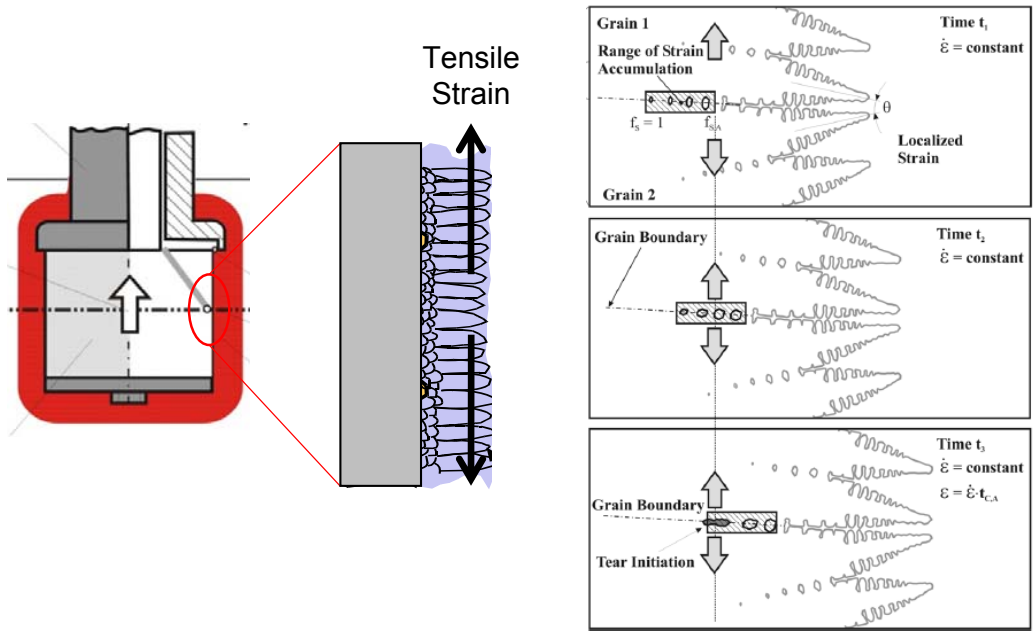
Cylinder prevents contraction of solidifying shell

SSCC Experimental Apparatus



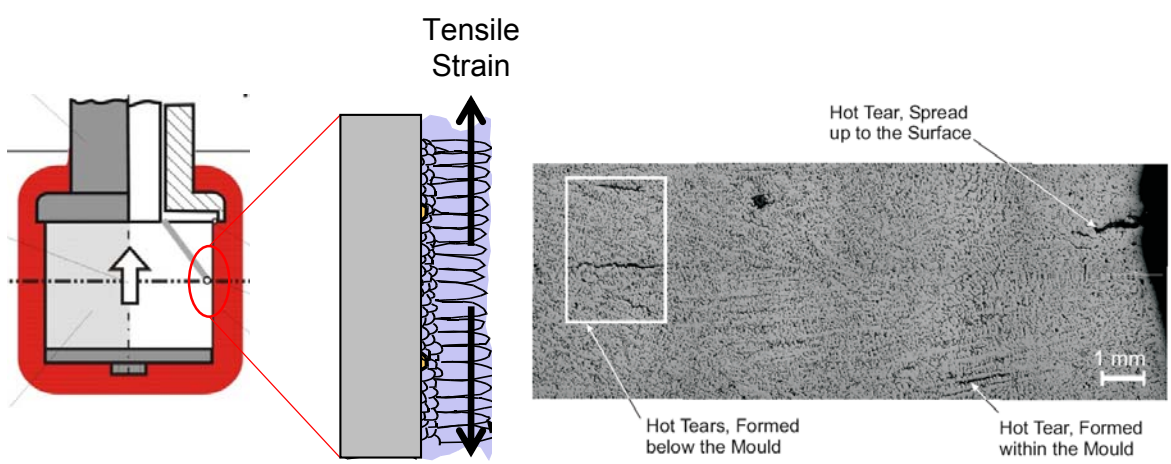
Tensile strains develop perpendicular to dendrite growth direction

SSCC Experimental Apparatus



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

SSCC Experimental Apparatus



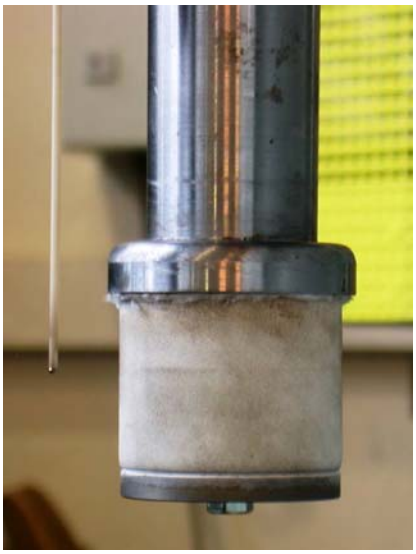
Bernhard C.:*Anforderungen an prozessorientierte Heißrissbildungsmodelle* BHM, Vol. 149 (2004), 90-95

SSCC Test



Images courtesy of R. Pierer

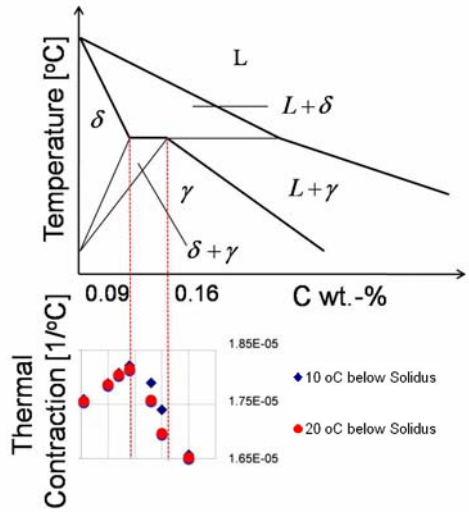
Removed Solidified Shell



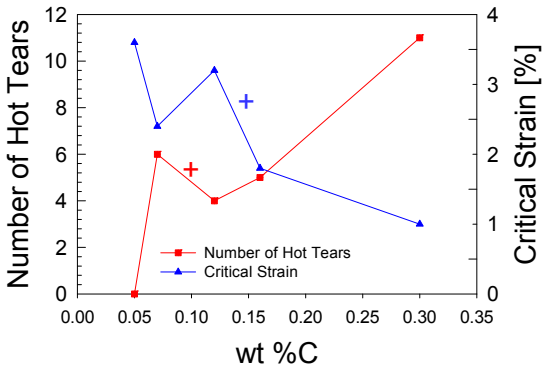

Images courtesy of R. Pierer

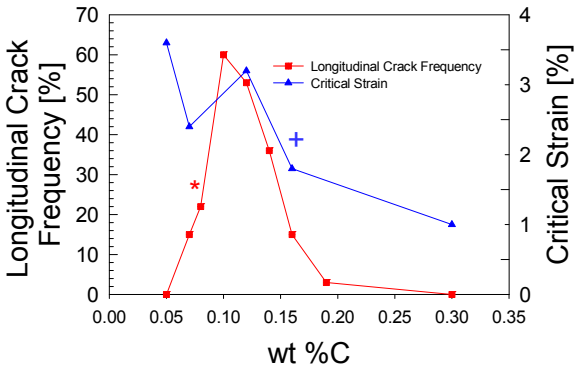
Experimental Data

- 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



Critical Strain to Form Hot Tears and Longitudinal Cracks





+ Pierer R., Bernhard C. and Chimani C., "A contribution to hot tearing in the continuous casting process", *La Revue de Metallurgie-CIT, February 2007, pp. 72-83.*

* Mazumdar, S. and Ray, S. K., "Solidification control in continuous casting of steel", *Sādhanā, Vol. 26 (1-2), 2001, pp. 179-198.*

Experimental Steel Compositions

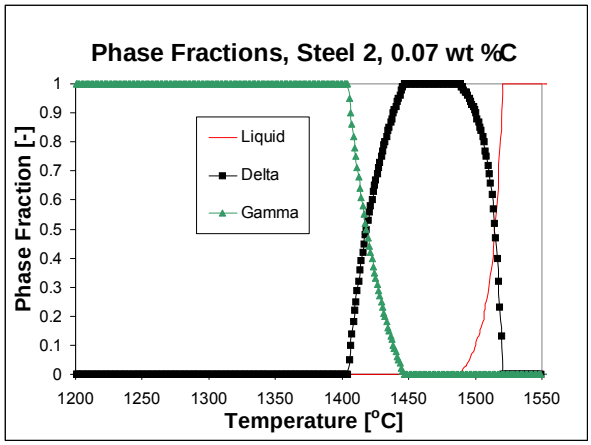
Steel No.	C (Wt %)	Si (Wt %)	Mn (Wt %)	P (Wt %)	S (Wt %)	Ni (Wt %)	C_p (Wt %)
1	0.05	0.29	1.52	0.012	0.004	0.017	0.07
2	0.07	0.27	1.51	0.012	0.004	0.017	0.09
3	0.09	0.29	1.55	0.011	0.008	0.026	0.12
4	0.13	0.31	1.57	0.014	0.004	0.017	0.15
5	0.15	0.28	1.56	0.014	0.005	0.018	0.17
6	0.20	0.27	1.75	0.014	0.005	0.020	0.23

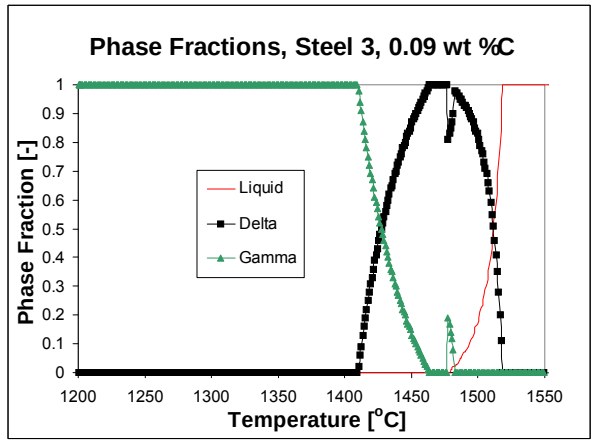
Thermo-mechanical Analysis

- Solve 2-D axisymmetric transient heat conduction equation and elastic-viscoplastic stress analysis
- 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 Fractions





$T_{liquidus}$ = 1520 °C
$T_{solidus}$ = 1488 °C
$T_{\delta\rightarrow\gamma,\ begin}$ = 1446 °C
$T_{\delta\rightarrow\gamma,\ end}$ = 1404 °C

$T_{liquidus}$ = 1518 °C
$T_{solidus}$ = 1478 °C
$T_{peritectic}$ = 1483 °C
$T_{\delta\rightarrow\gamma,\ end}$ = 1409 °C

Data from CON1D with Clyne-Kurz Segregation Model

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)

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

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

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

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

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

Modified Power Law Model for δ-ferrite (Zhu)

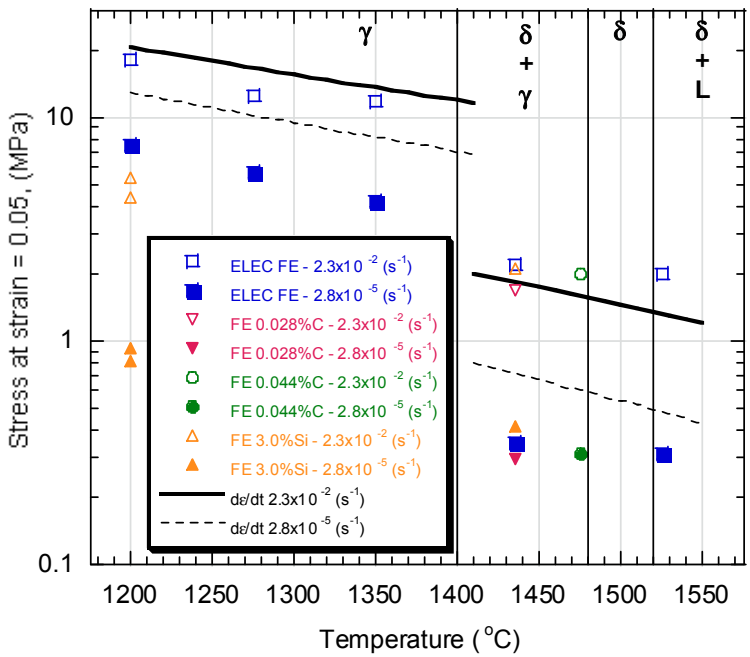
$$\dot{\varepsilon}(1/\sec.) = 0.1\left|\sigma(MPa)\Big/ f(\%C)\left(T(^oK)/300\right)^{-5.52}(1+1000\varepsilon)^m\right|^n$$

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

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

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

Constitutive Behavior of Steel



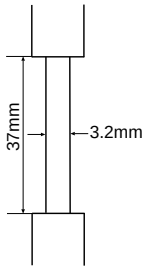
- *Lines:*

  Constitutive Model Predictions

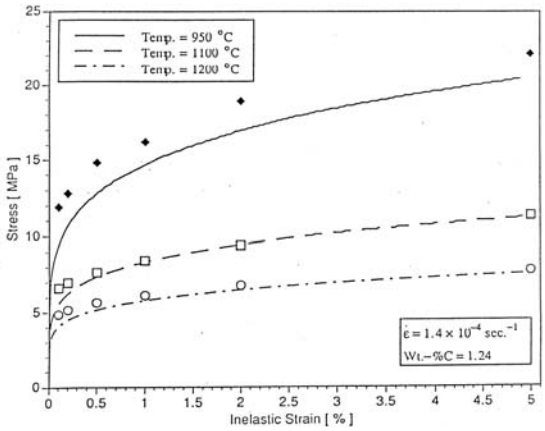
- *Symbols:*

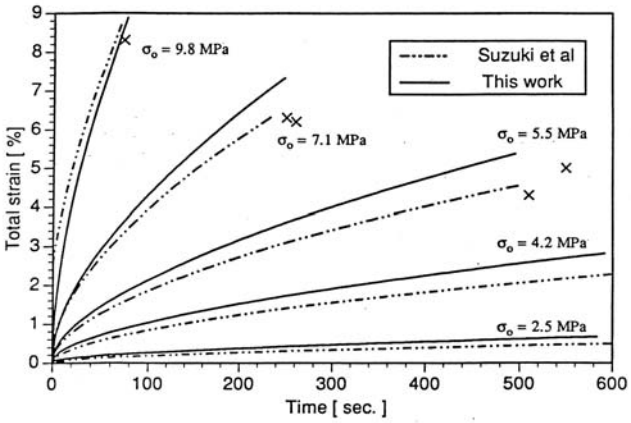
  *Wray measurements**

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



Constitutive Behavior of Steel





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

Model Validation

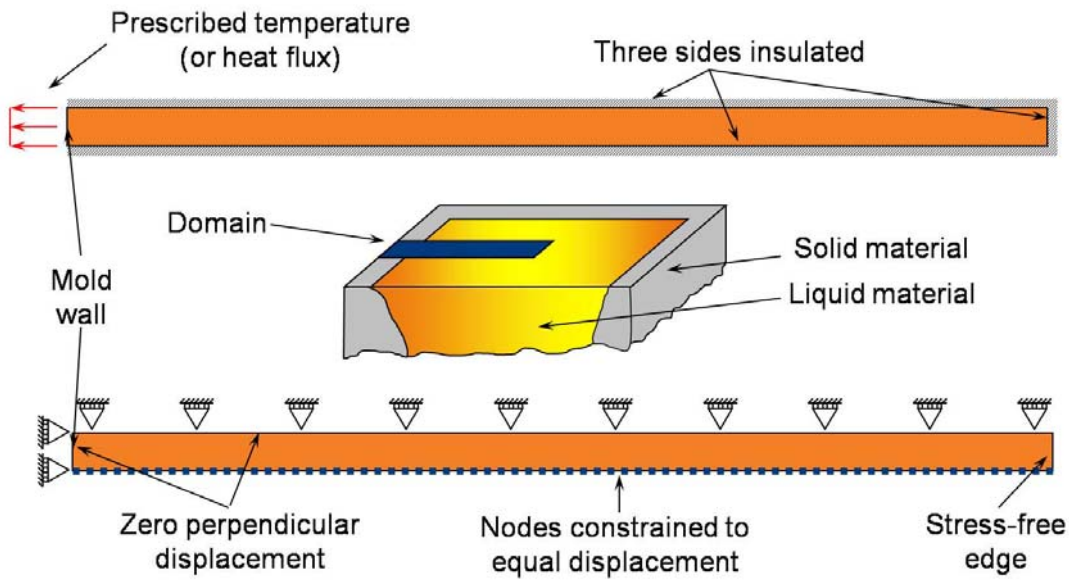
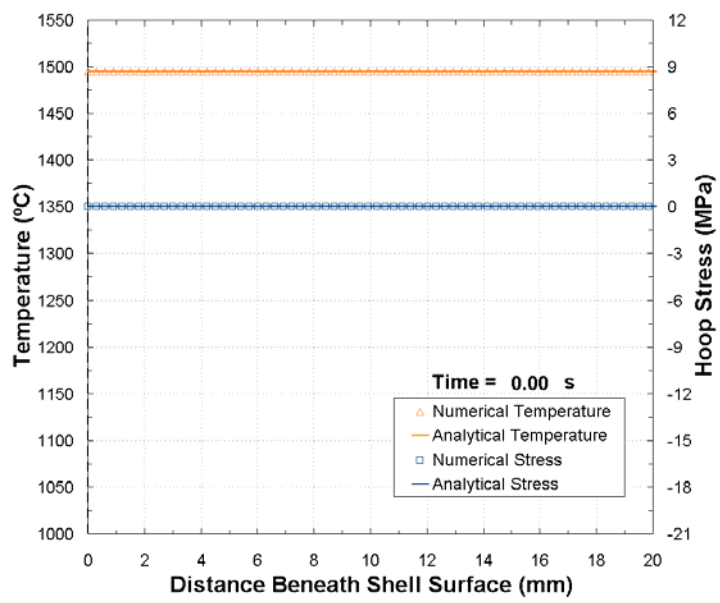


Image courtesy of L. Hibbeler

Comparison with Analytical Solution

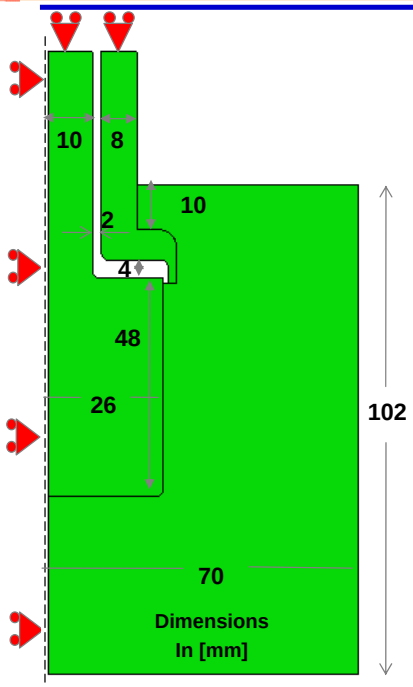
Property/Condition	Value
Density	7500.0 kg/m³
Specific heat	661.0 J/(kg·K)
Latent heat	272.0 kJ/kg
Thermal conductivity	33.0 W/(m·K)
Thermal expansion coefficient	20.0E-6 m/(m·ºC)
Poisson's ratio	0.3 –
Initial temperature	1495.0 ºC
Liquidus temperature	1494.48 ºC
Solidus temperature	1494.38 ºC
Mold temperature	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

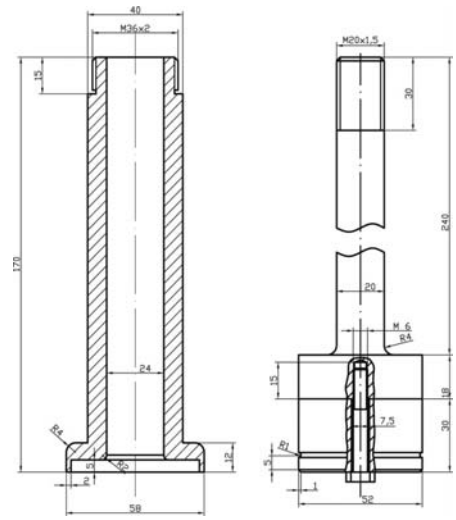
Courtesy of L. Hibbeler



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.

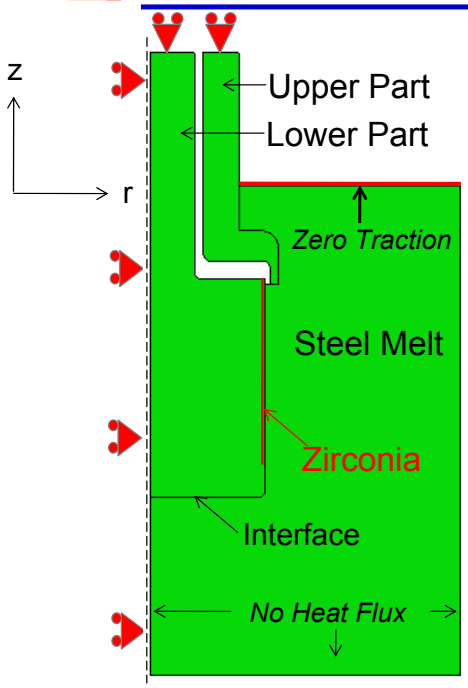
Model Domain





SSCC Design

Boundary Conditions



4-node axisymmetric elements

$T_{initial,\ steel\ melt}$ ~1540 ^oC
$T_{initial,\ test\ cylinder}$ =25 ^oC

Interface Conditions:

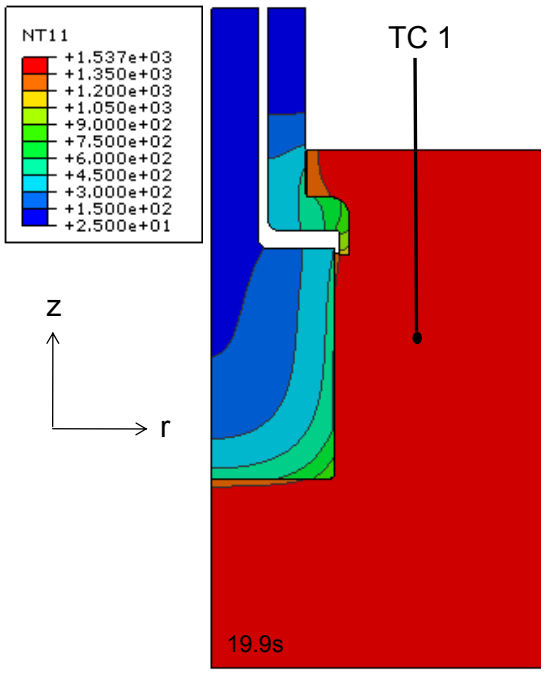
<u>Heat Transfer</u>

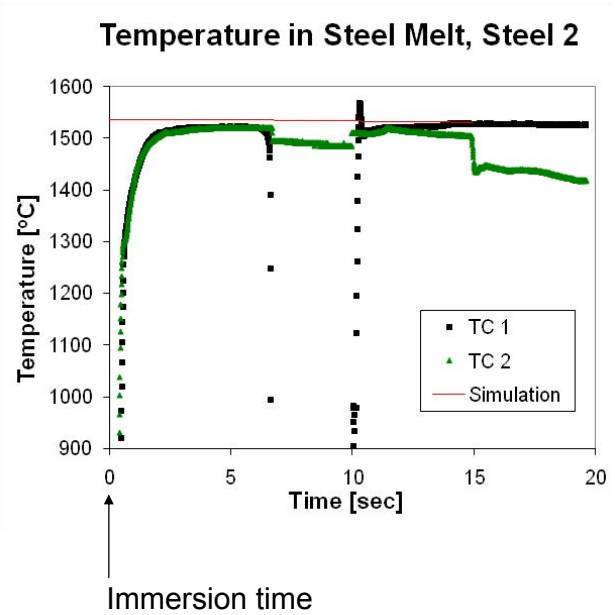
- Heat Transfer Coefficient = 1850 W/m/^oC

<u>Stress</u>

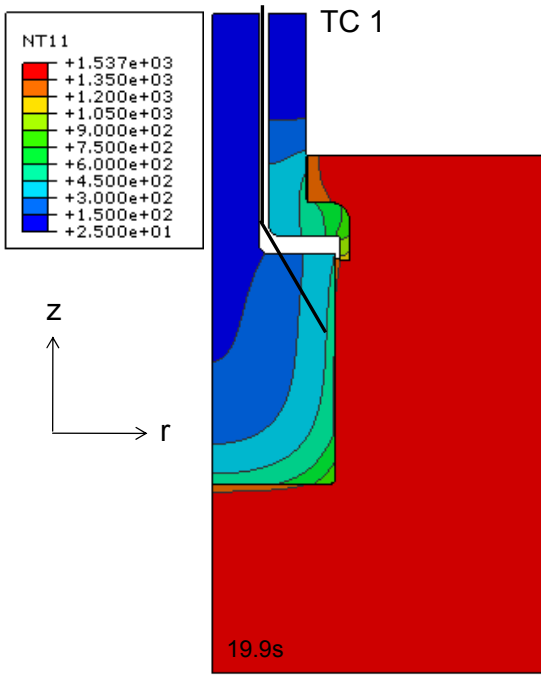
- Coefficient of Friction = 0.3

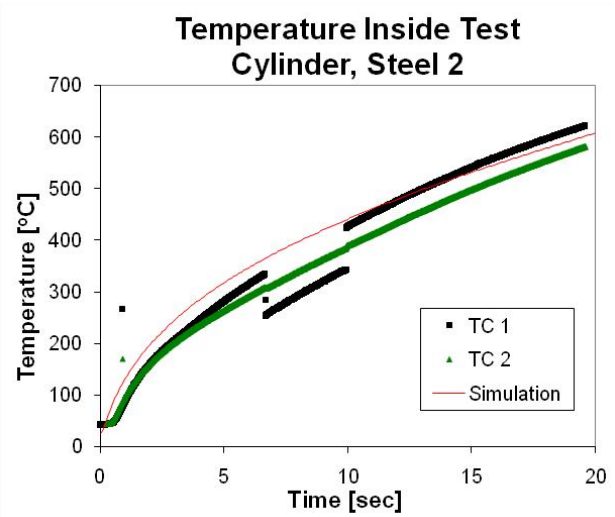
Temperature History – Melt, Steel 2



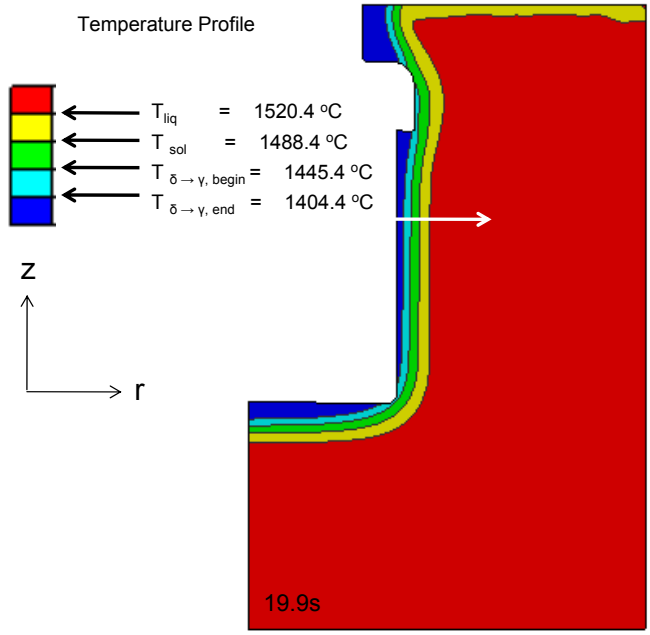


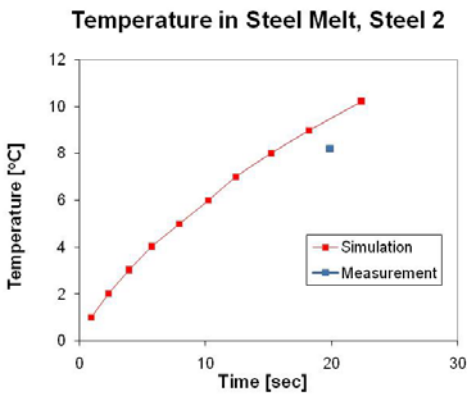
Temperature History – Cylinder, Steel 2



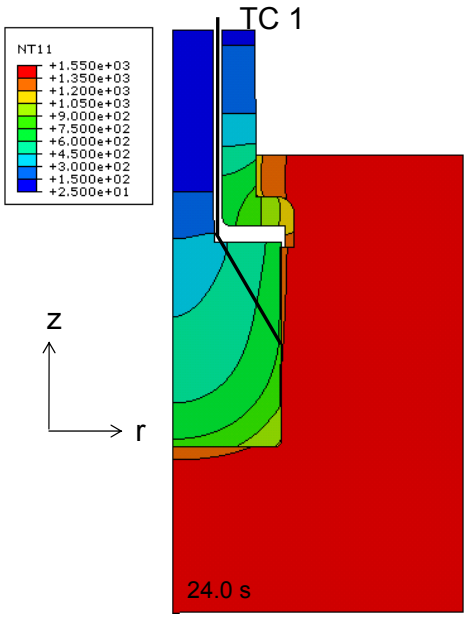


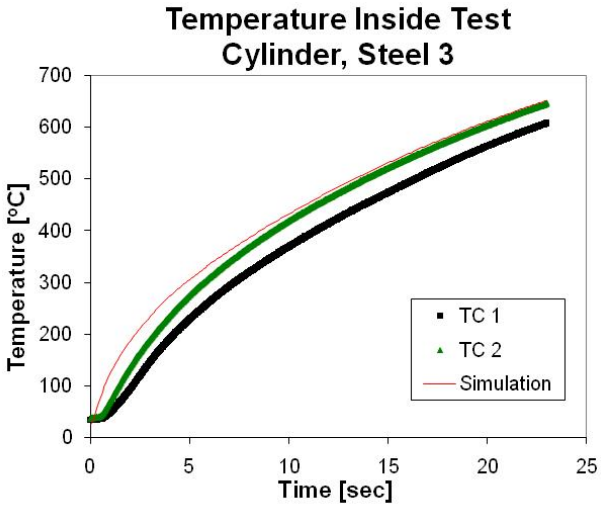
Shell Growth Profile, Steel 2



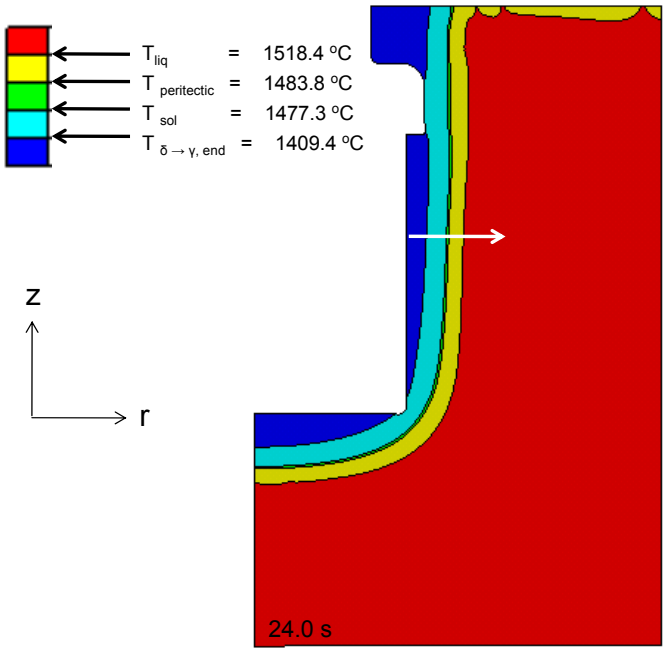


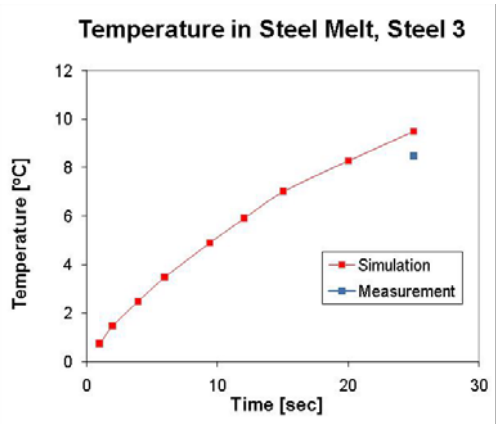
Temperature History – Cylinder, Steel 3



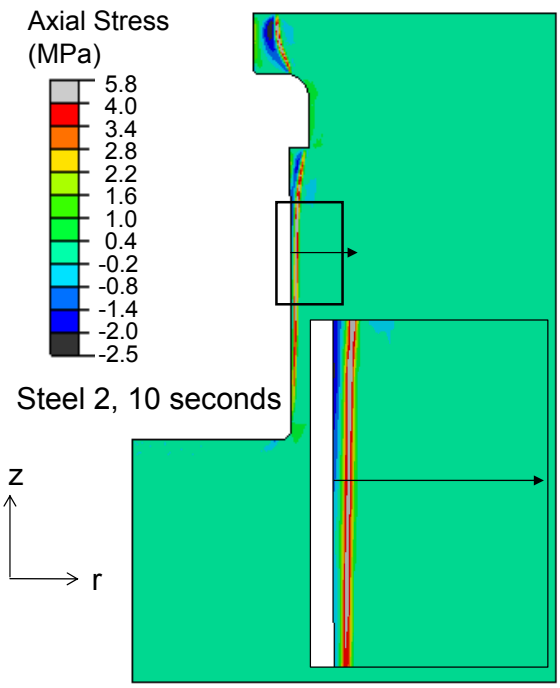


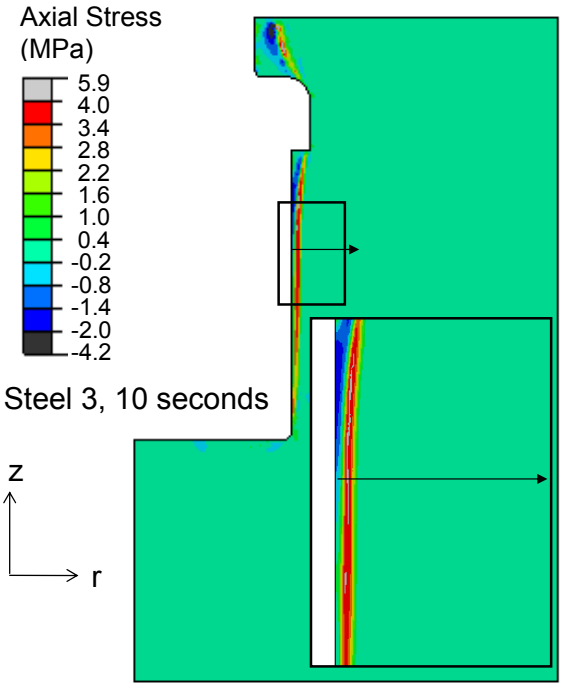
Shell Growth Profile – Steel 3





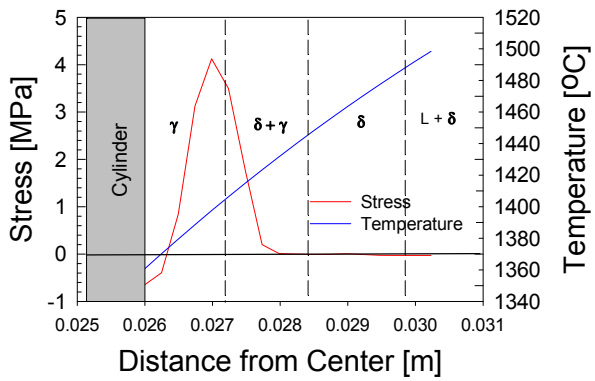
Phase Dependant Shell Strength



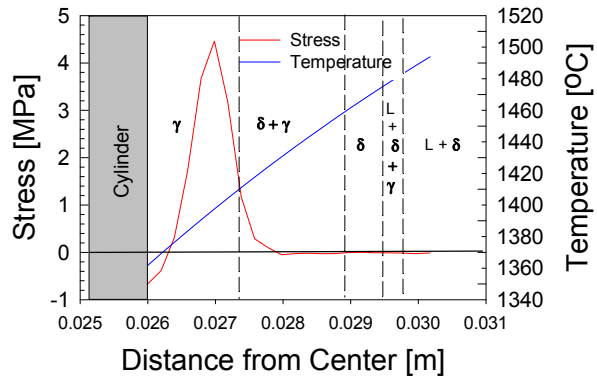


Shell Strength is Phase Dependant

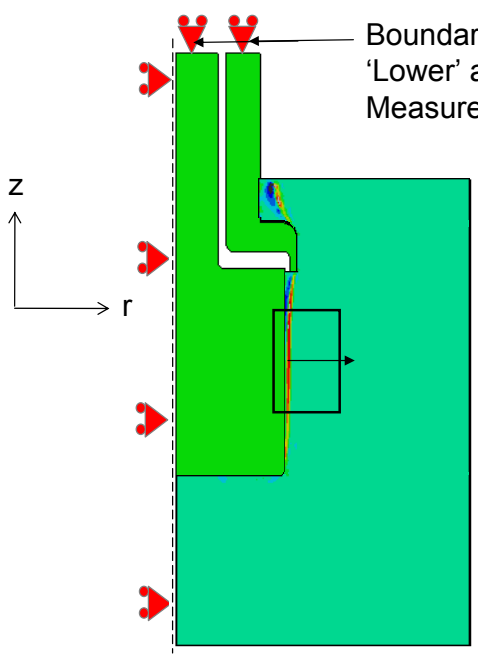
Steel 2, 10 seconds



Steel 3, 10 seconds

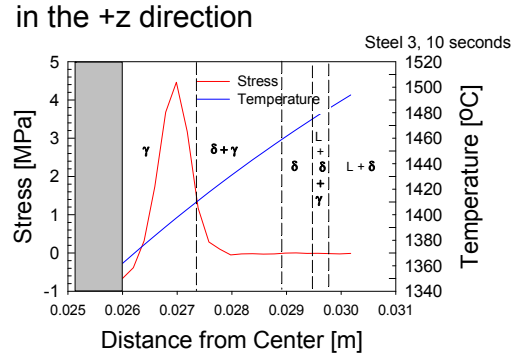


Solidification Force

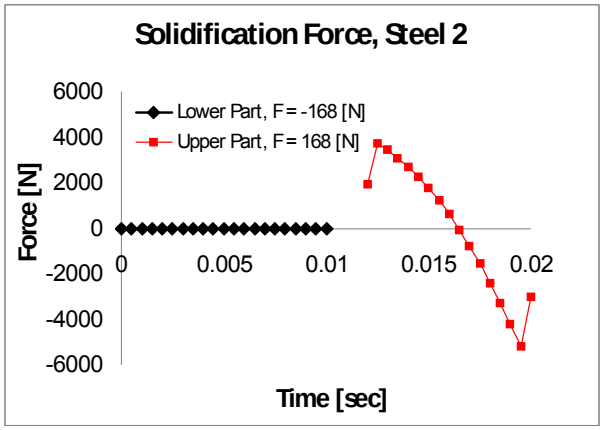


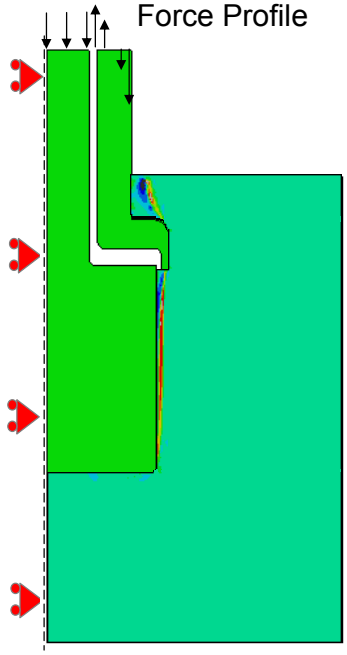
Boundary Conditions prevents 'Lower' and 'Upper' part from moving. Measure the reaction force here.

Shell stress is cumulatively acting in the +z direction



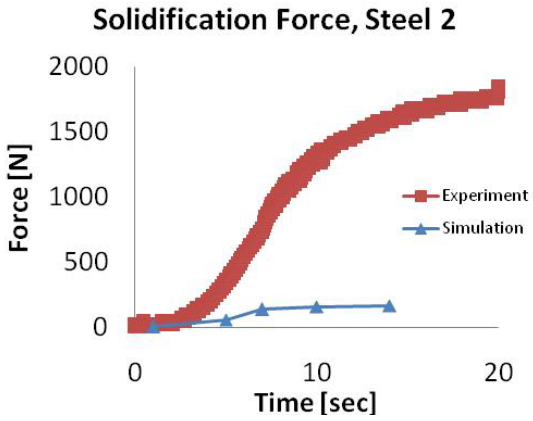
Plot of Reaction Force of Lower and Upper Parts

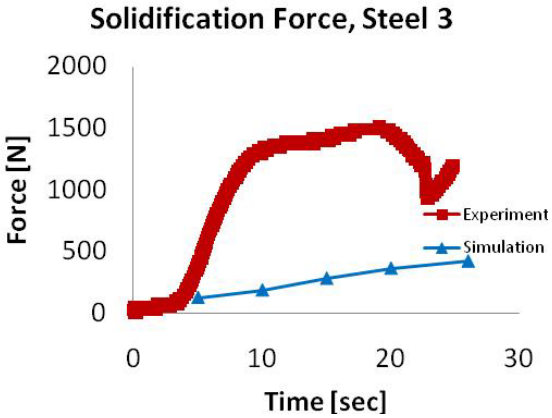




Force in Shell = - Reaction Force In Lower Part = Reaction Force In Upper Part

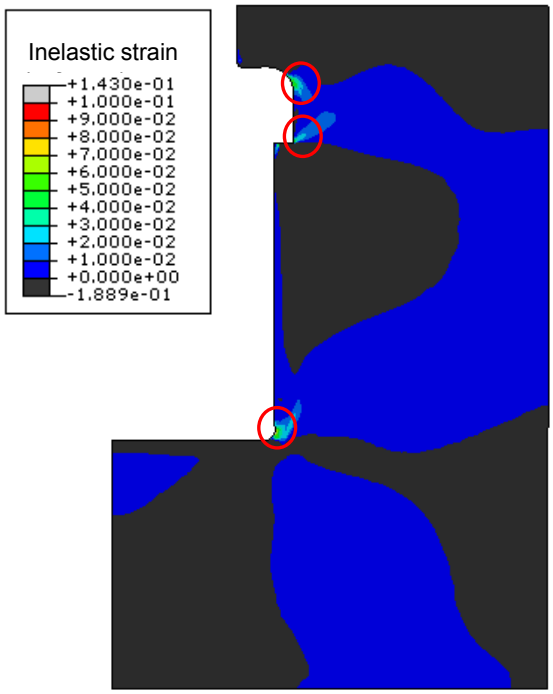
Solidification Force





Simulation underestimates the measured force. Presents an opportunity to improve constitutive model.

Calculation of Critical Strain – Steel 2



Regions of large tensile strain.

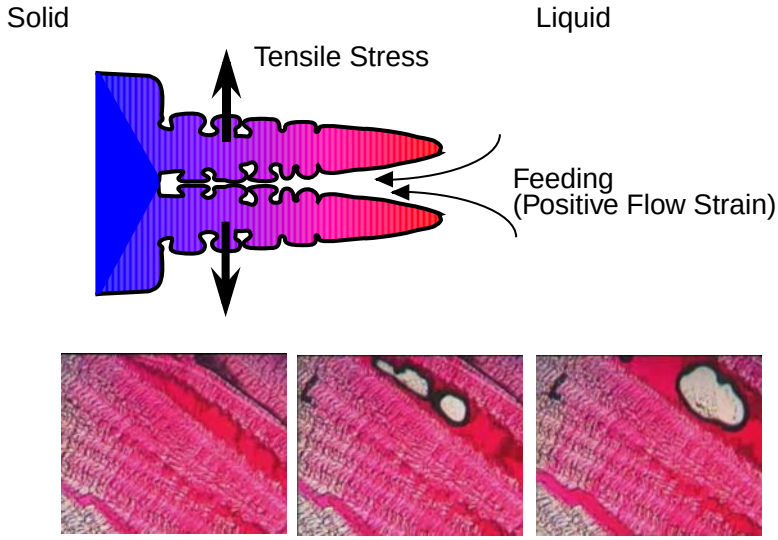
Calculation of Critical Strain

$$\varepsilon_{crit} = \frac{0.02821}{\dot{\varepsilon}^{0.3131} \Delta T_B^{0.8638}} \quad *$$

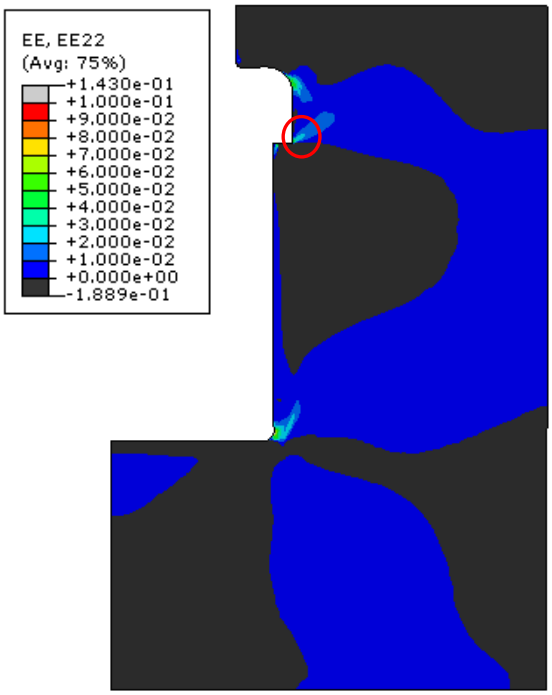
- Equation fit over large range of strain rates and cooling rates
  - (5 – 90 x 10^{-4} 1/sec)
- ΔT_B = Brittle temperature difference
  - Temperature difference between 90% and 99% solid fraction
- Strain rate found from simulation

* Won, MY, Yeo, TJ, Seol, DJ and Oh, KH, "A New Criterion for Internal Crack Formation in Continuously Cast Steels", *Met. Trans. B,* Vol. 31B, 2000, pp. 779-94

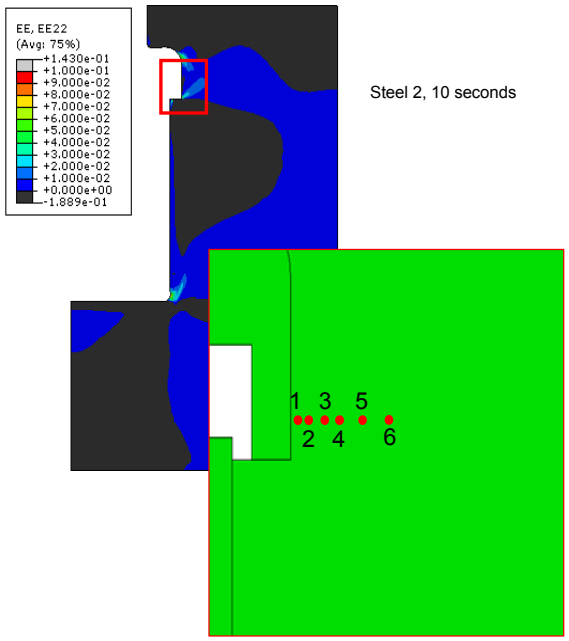
Hot Tear Formation

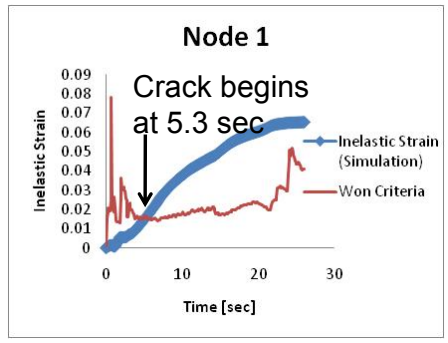


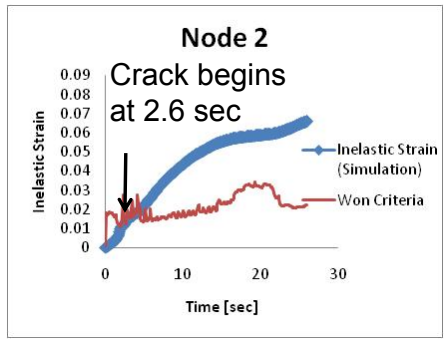
Won Criteria Exceeded in this Region First – Steel 2



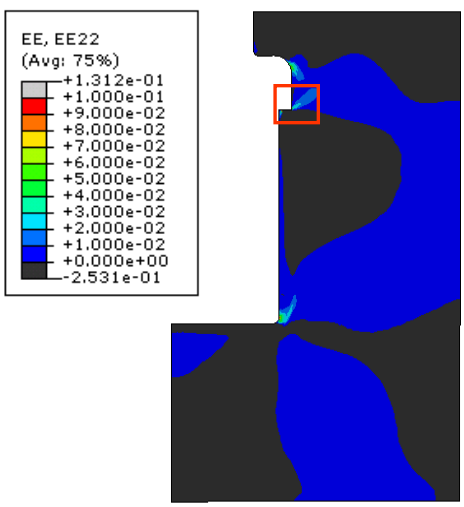
Won's Criteria is Time/Space Dependant

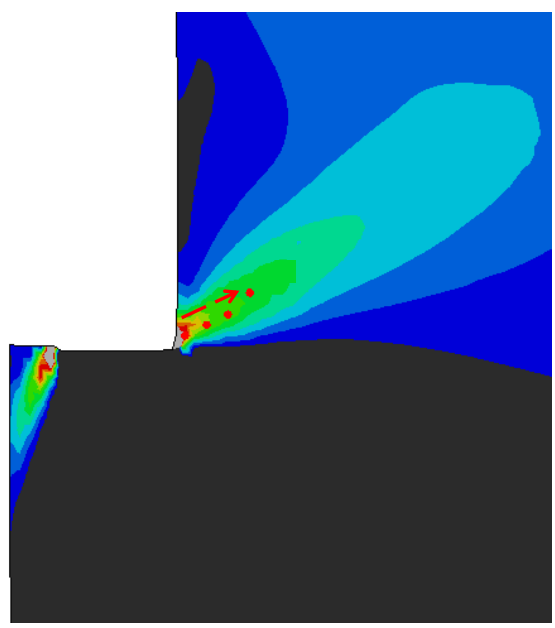






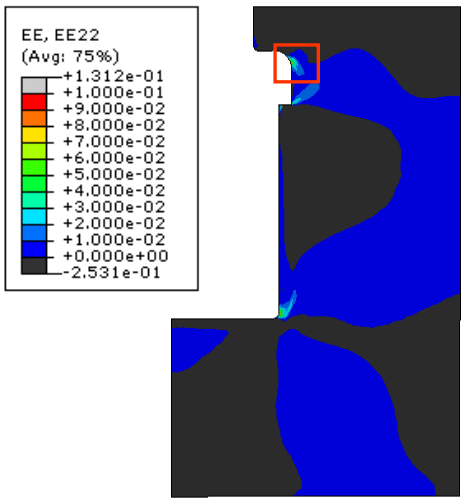
Steel 2 Crack Formation

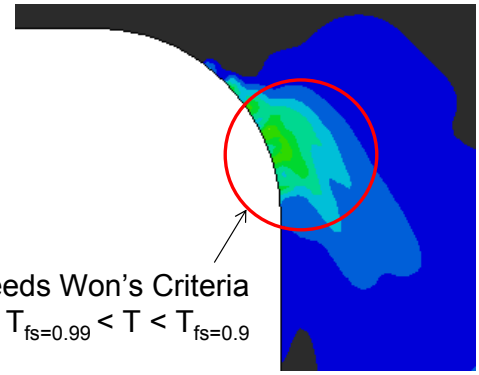




Phase: Solid, 100 % δ-ferrite
Mode: Starts at surface (5.3 [sec]), stops growing at 8.3 [sec].

Steel 2 Hot Tear Formation

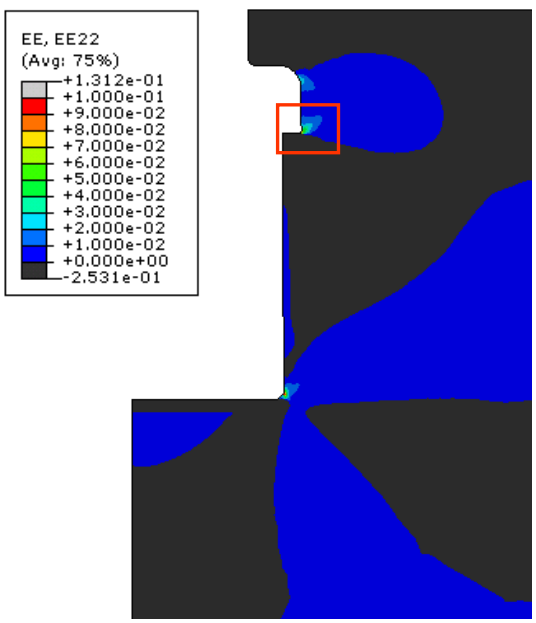


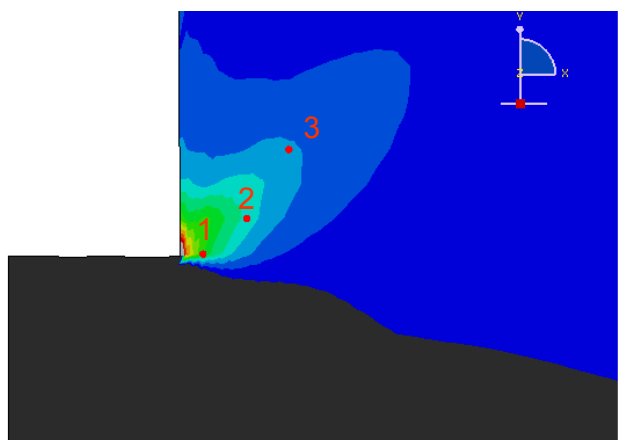


Exceeds Won's Criteria with $T_{fs=0.99} < T < T_{fs=0.9}$

Forms Hot Tears

Steel 3 Defect Formation

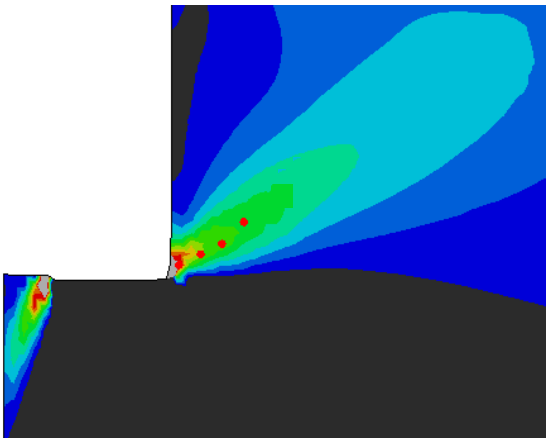


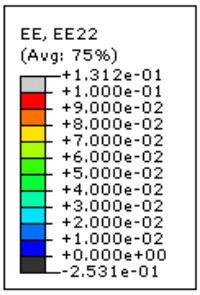


Node	Time [sec]	Temperature [°C]	Solid Fraction
1	1.4	1513	0.59
2	4.7	1494	0.89
3	11.5	1461	1

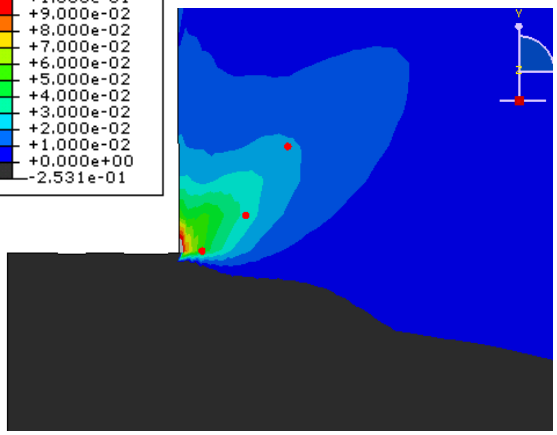
Comparison of Defects

Steel 2, 10 seconds

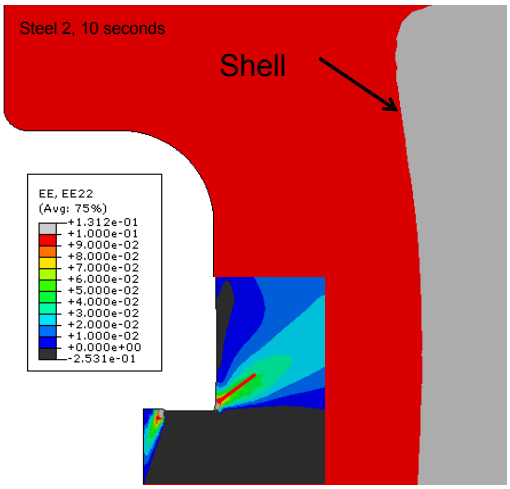




Steel 3, 10 seconds

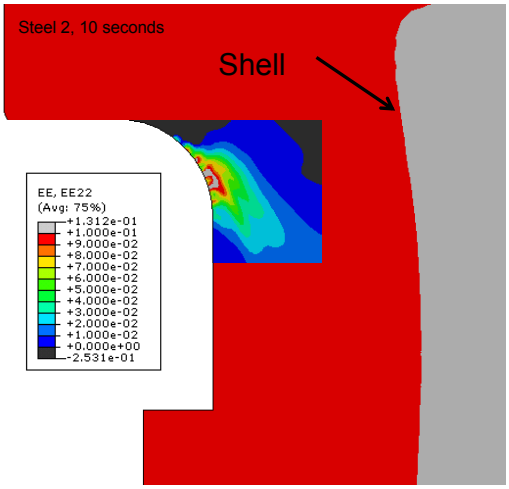


Good Agreement - Crack



Crack is similar location and length, but oriented differently.
Solution: Enhance coupling of temperature and displacement.

Good Agreement – Hot Tears



The simulation is predicting hot tears where they are experimentally seen.

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

Defects are predicted in regions of high surface temperature with local strain concentration. The model is capable of differentiating hot tears from cracks.

This work is a first step to combine experiments and models to develop criteria for predicting cracks and hot tears in solidifying steel

Future Work

Enhance temperature-displacement coupling.

Develop constitutive model that matches experimental force curve.

Perform simulations for more steel grades.

Acknowledgments

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