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Solidification Stresses and Hot Tearing in Solidifying Steel Shells

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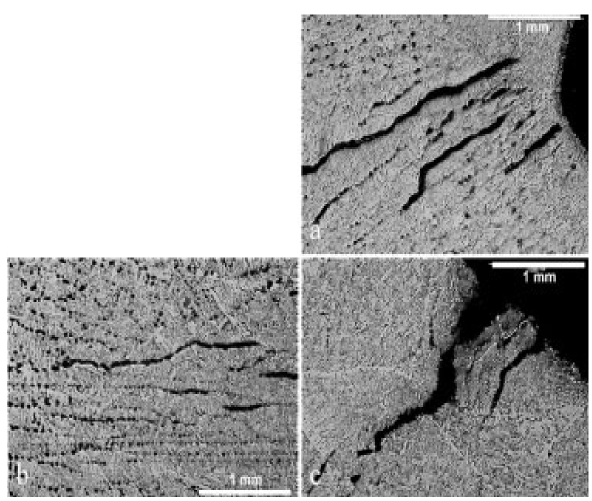
Background

- Stress develops in solidifying shell in CC 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

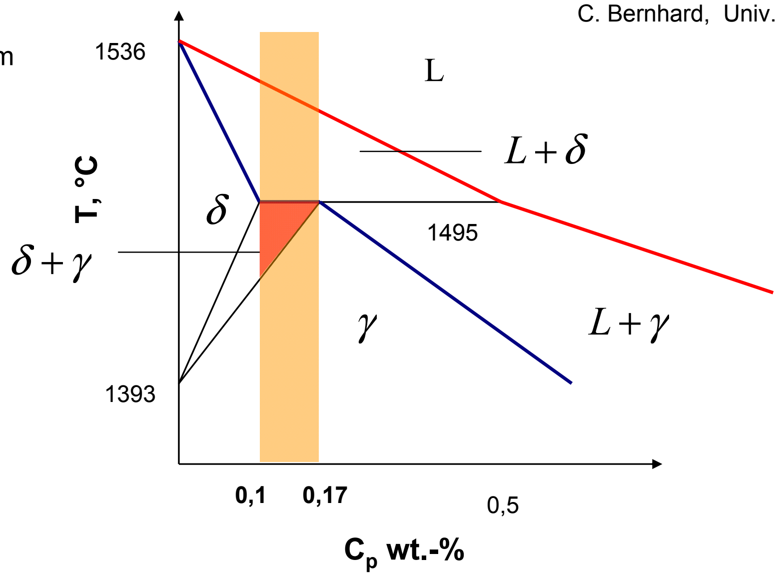


C. Bernhard and G. Xia, *Ironmaking and Steelmaking*, 2006

Steel Shrinkage Varies with Composition

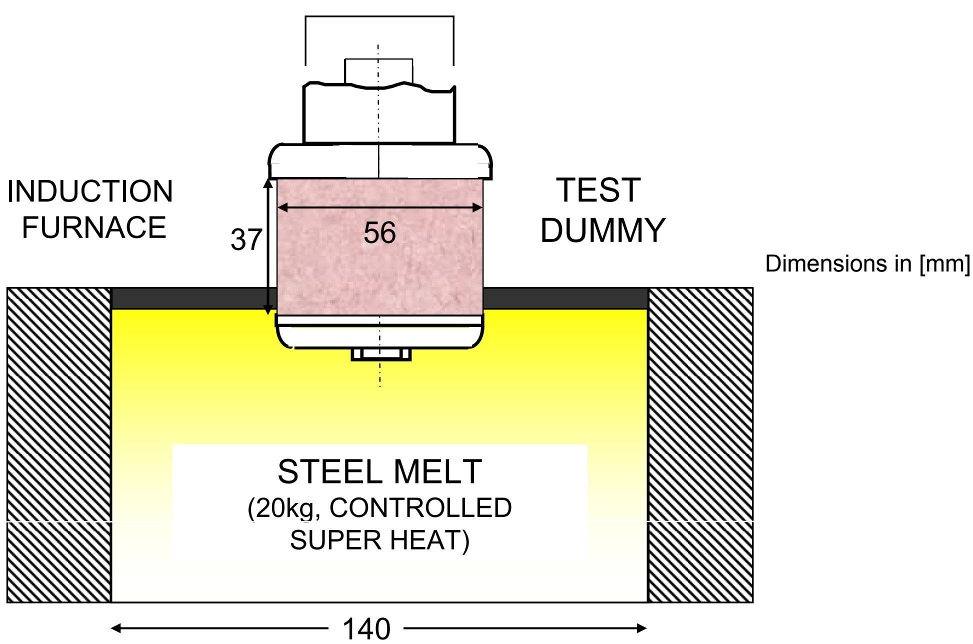
C. Bernhard, Univ. Leoben, 2002

Fe-C equilibrium phase diagram



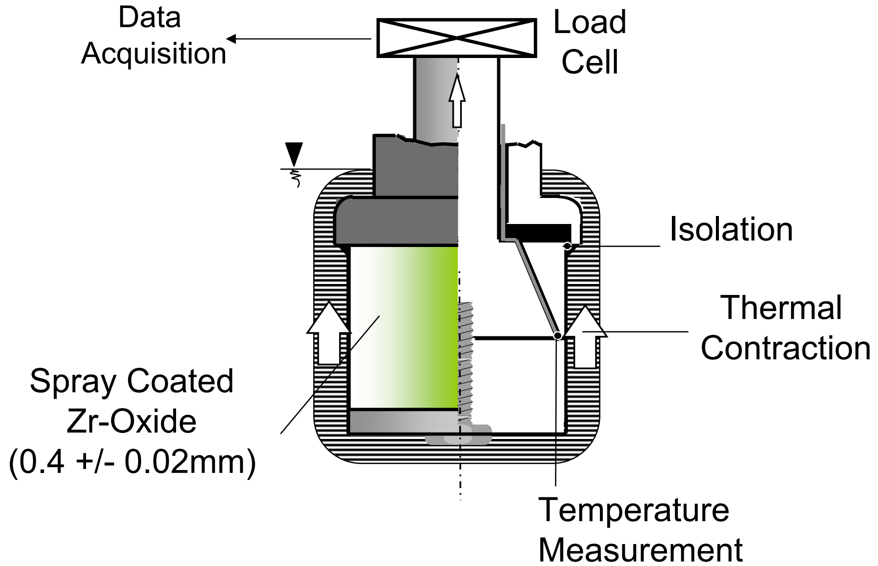
$$c_p = \%C + 0.04\cdot\%Mn + 0.04\cdot\%Ni - 0.1\cdot\%Si - 0.04\cdot\%Cr - 0.1\cdot\%Mo$$

SSCT Experiment



C. Bernhard, Univ. Leoben, 2007

SSCT Experiment Operation



C. Bernhard, Univ. Leoben, 2007

Measurements from Each Experiment

- Alloy composition
- Pour temperature
- Temperature Histories (2 thermocouples)
  - Inside Cylinder (2mm from exterior face)
  - Melt (16-20mm from exterior face)
    - Varies with each test
- Final Shell Thickness
- Force History (load cell)

Objectives

1) Create thermal-mechanical model of temperature & stress-strain behavior of the steel solidification experiment (cylinder & shell)

2) Validate model with all measurements

3) Plot model stress / strain histories to better understand experiment

4) Evaluate crack criteria

- compare model predictions based on previous crack criteria with crack measurements (this work and previous)

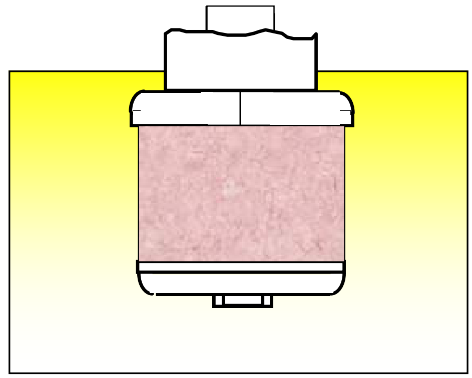
Solution Procedure

- Thermal stress analysis model in ABAQUS
  - Temperature determines stress
  - Employ user subroutines for constitutive equations and 2-level local integration method (Koric, 2006)
    - Temperature, strain-rate, phase-, and C content dependant

Model Assumptions

Assumptions:

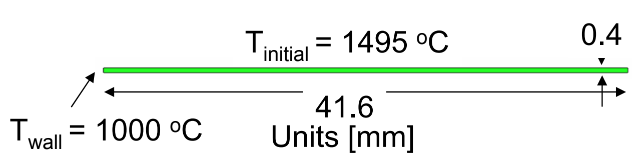
- axisymmetry
- no contact resistances at interface
- no heat transfer prior to t=0
- melt TC indicates time of start and end of test
  - force data used in the event TC data failure
- no heat loss to container walls or top surface
- initial temp-gradient across Zr
  - for stress convergence
- shell thickness defined at solid fraction = 0.1
- zero displacement of cylinder at immersion surface



Model Validation – Analytical Solution

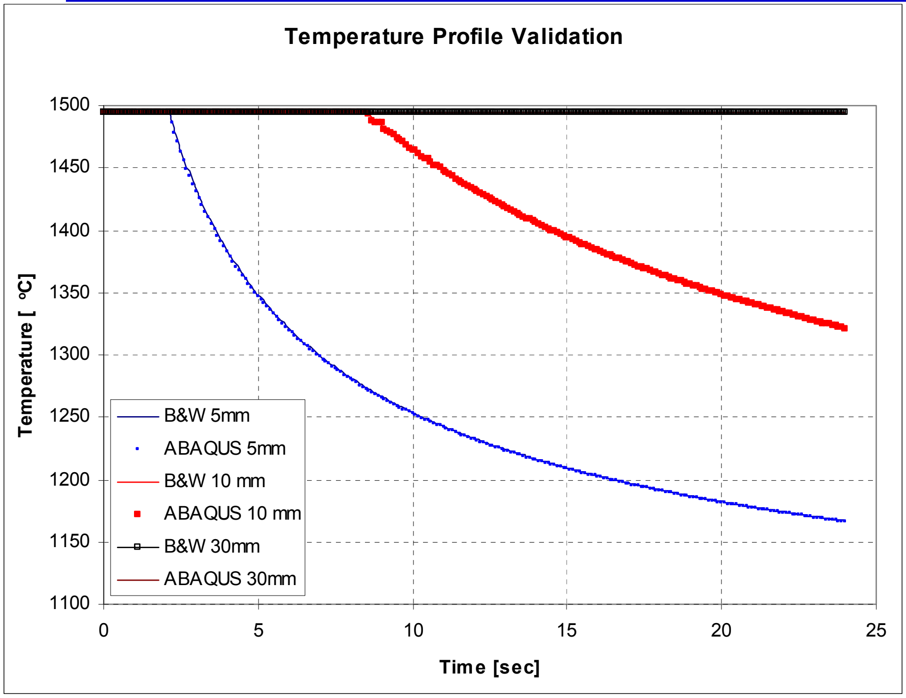
Property	Value	Units
Density	7500	kg/m^3
Specific Heat	661	J/(kg-K)
Latent Heat	272	kJ/kg
Thermal Conductivity	33	W/(m-K)
Coefficient of Expansion	2.00E-05	$m/(m^oC)$
Poisson's Ratio	0.3	--
Yield Stress at Mold Temp.	20	MPa
Yield Stress above Solidus Temp.	35	kPa
Elastic Modulus at Mold Temp.	40	GPa
Elastic Modulus above Solidus Temp	15	GPa
Initial Temperature	1495	^oC
Mold Temperature	1000	^oC

- Boley and Weiner

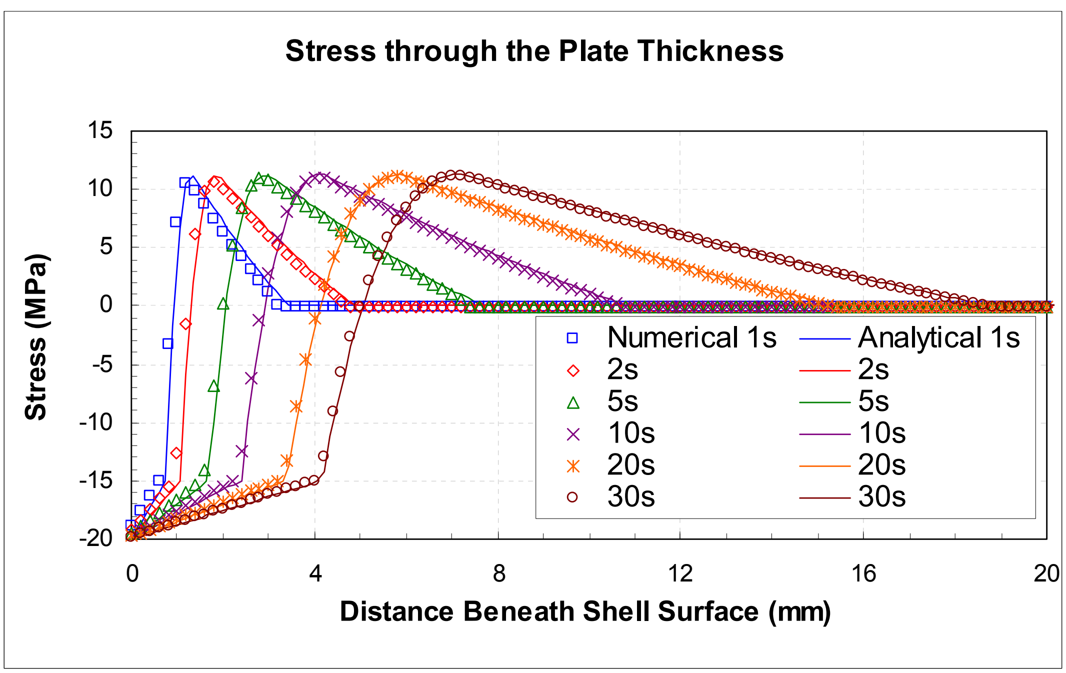


T_{sol} = 1494.38 °C
T_{liq} = 1494.48 °C
T_{wall} = 1000 °C, h = 220 $kW/(m^2\text{-}K)$

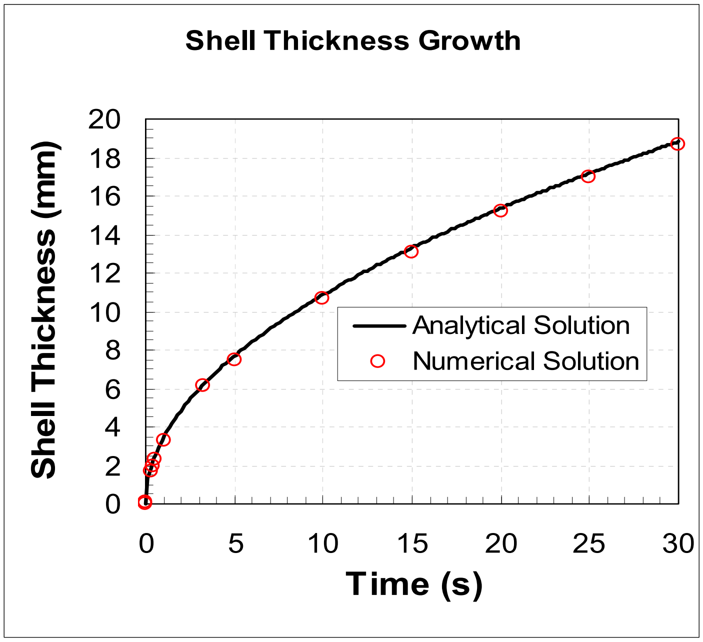
Temperature Validation



Stress Validation

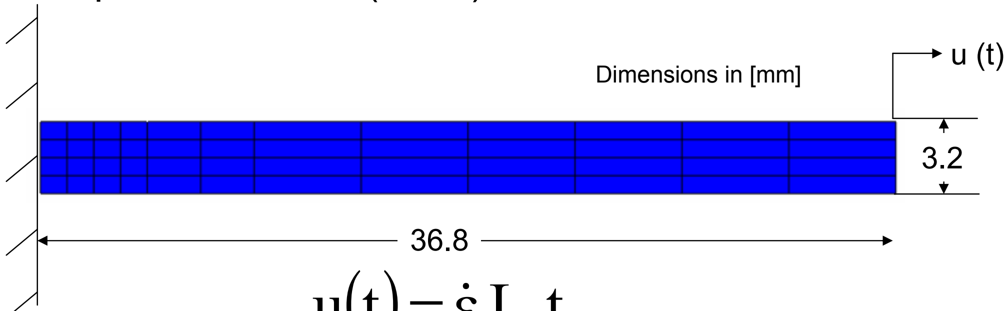


Shell Growth Validation



Verification – Tension Test

- Data based on experiments by Wray (1976)
- Abaqus with UMAT (Koric)



$$u(t) = \dot{\varepsilon} L_0 t$$

- Temperatures – 950 ^{o}C, 1100 ^{o}C
- Strain Rate – 1.4 x 10^{-4} [1/sec]

Constitutive Equations for Solid Steel

- Kozlowski III model for austenite [Kozlowski, 1991]

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

$$f_1(T(^\circ K)) = 130.5 - 5.128\times10^{-3}T(^\circ K)$$

$$f_2(T(^\circ K)) = -0.6289 + 1.114\times10^{-3}T(^\circ K)$$

$$f_3(T(^\circ K)) = 8.132 - 1.54\times10^{-3}T(^\circ K)$$

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

- Modified power law for delta-ferrite [Parkman, 2000]

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

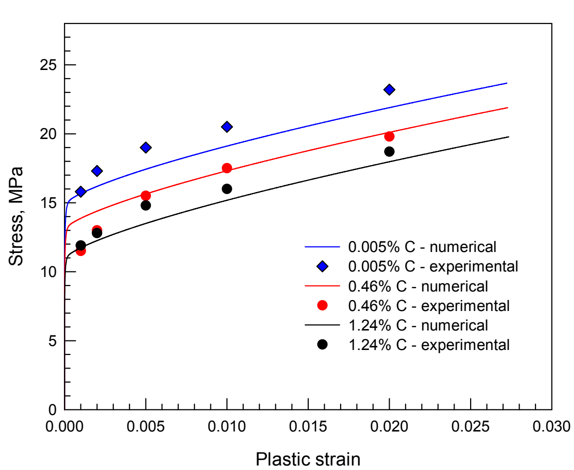
$$f(\%C) = 1.3678\times10^4(\%C)^{-5.56\times10^{-2}}$$

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

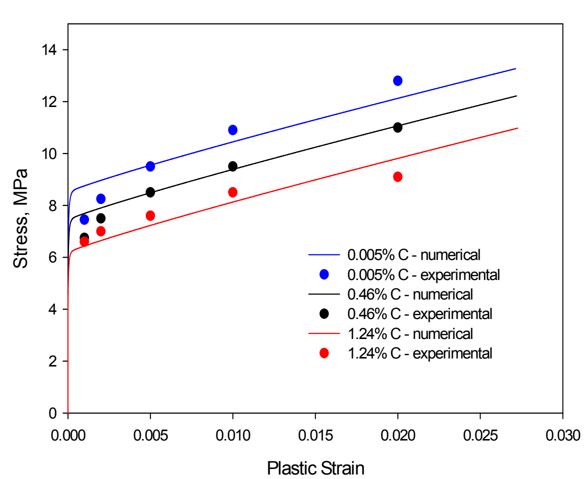
$$n = 1/1.617\times10^{-4}T(^\circ K) - 0.06166$$

Tensile Test Simulation

950 °C, 1.2 x 10^{-4} 1/s



1100 °C, 1.2 x 10^{-4} 1/s



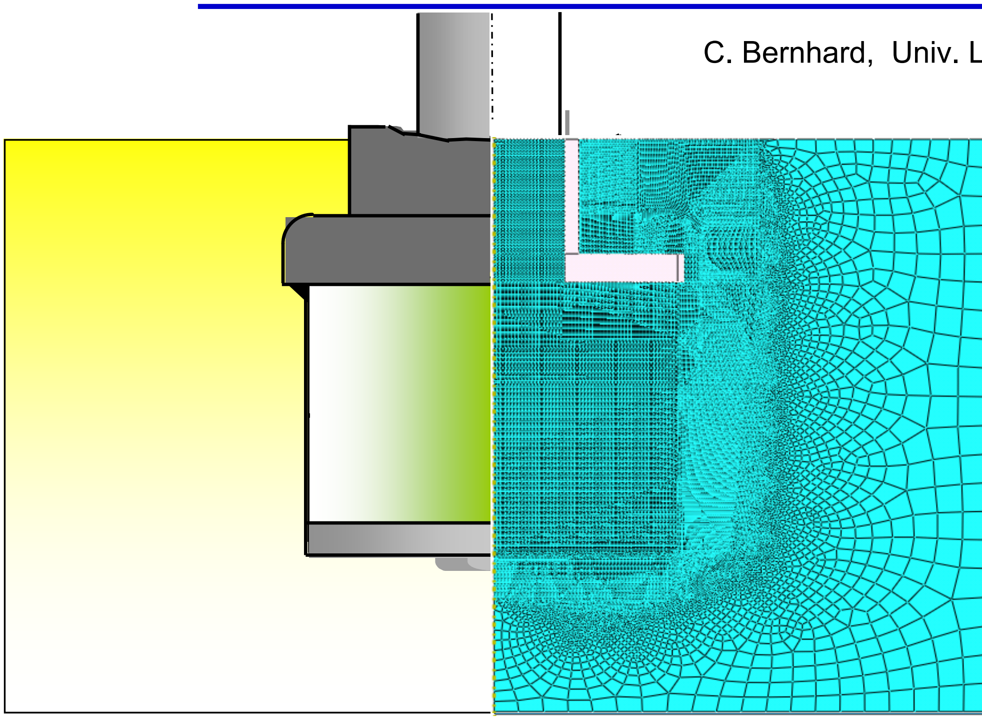
Provided Data

- Alloying content
  - C, Si, Mn, P, S, Ni
    - Combined to form 'Cp'
      - Crack formation sensitive to this factor
- Temperature
  - 2 locations in the test cylinder
    - 2mm from molten steel interface
  - 2 locations in the steel melt
    - Test dependent
      - 16-20 mm from test cylinder
- Shell Thickness
- Force

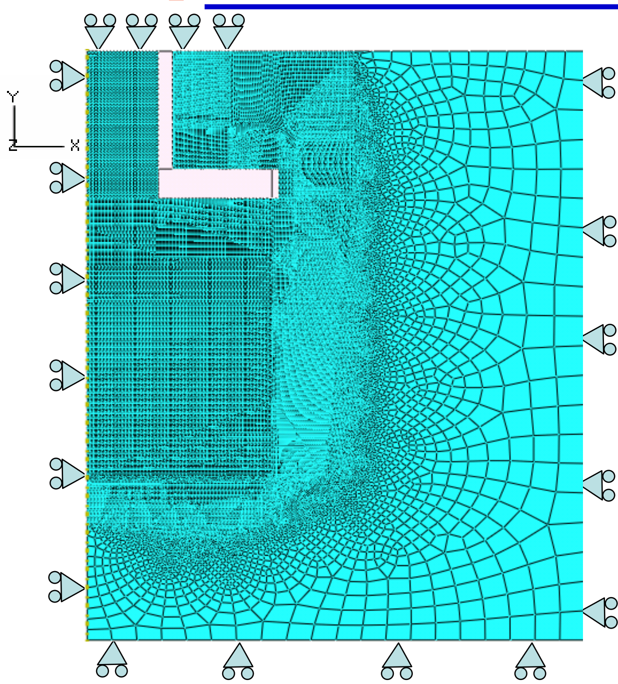
Image Source:
http://www.xnqy.cn/shebei1-e.htm

SSCT Model Domain

C. Bernhard, Univ. Leoben, 2007



2D Domain of Experimental Apparatus



No flux boundary conditions

No axial (y) displacement at top face of the cylinder

Axisymmetric elements (4 nodes)

$T_{initial,\ steel\ melt}$ ~1540 °C (1535-1548)
$T_{initial,\ test\ cylinder}$ =25 °C

0.04mm plasma-sprayed zirconia layer at test cylinder and melt interface

Mesh size biased to regions of solidification and large temperature gradients

Experimental Steel - Composition

Data Source: University of Leoben

Steel No.	C	Si	Mn	P	S	Ni	C_p
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

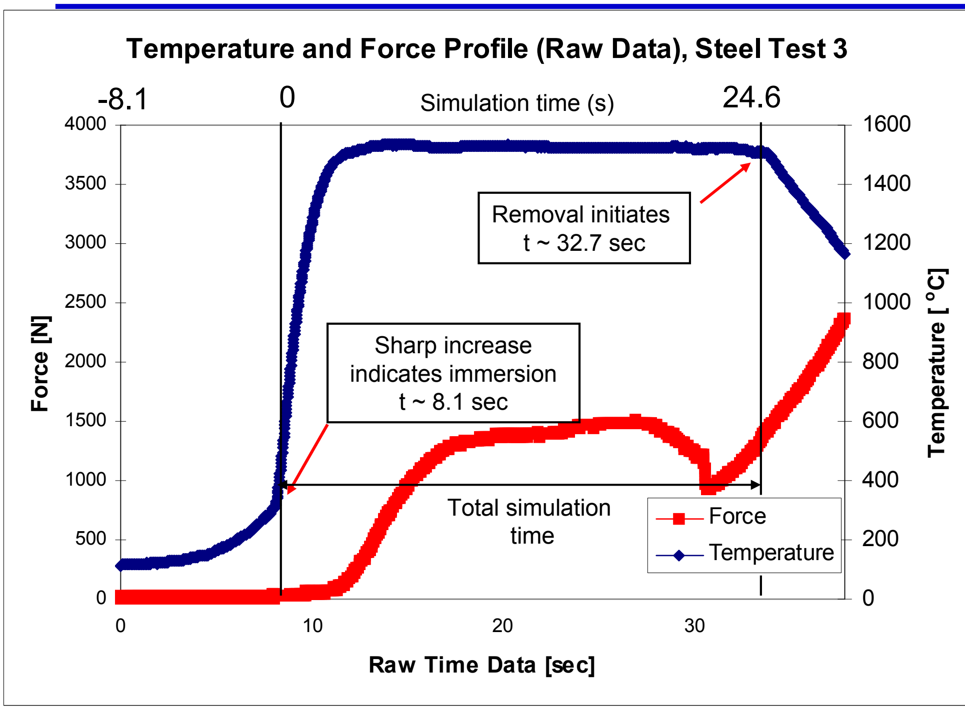
- Alloying content in terms of percentages

Background – Experimental Conditions

Test #	Cp	Immersion Time* [sec]	Shell Thickness [mm]	Temperature (Pour, Liquidus, Solidus) [°C]
1	0.07	24.7	8.8	1547 1521.5, 1494
2	0.09	19.6	8.76	1537 1520.1, 1486.6
3	0.12	24.6	8.5	1548 1518.1, 1476.3
4	0.15	20.3	10.14	1543 1514.8, 1470.2
5	0.17	18.7*	8.9	1535 1513.5, 1467.8
6	0.23	19.8*	8.75	1545 1508.7, 1454

*(Derived from Melt TC, except tests 5&6 used estimated finish time)

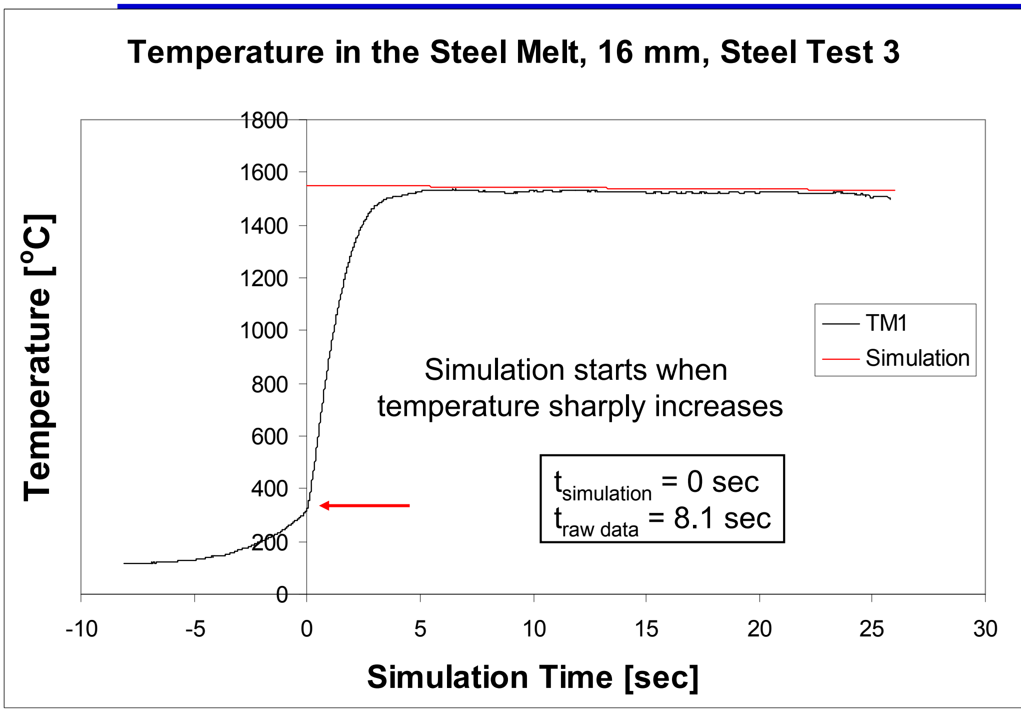
Sample Data File



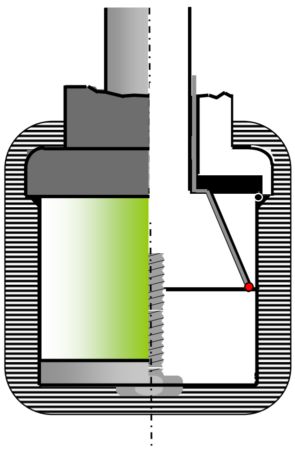
Data and Simulation Comparison

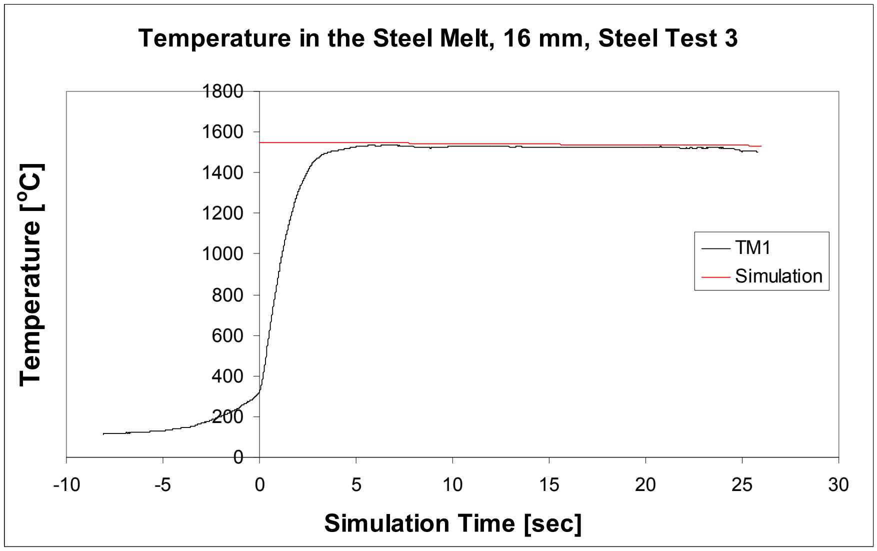
- Temperature history
  - Immersion (raw data, $t \neq 0$) indicates time at which simulation begins (simulation time, $t = 0$)
- Test completed when:
  - 1) Melt thermocouple temperature decreases
  - 2) Force data decreases (indicated by those running the experiment)
- Neglect transient effect of immersing and extracting
  - ~2.5 seconds for immersion
  - ~2.5 seconds for extraction

Simulation Initiation



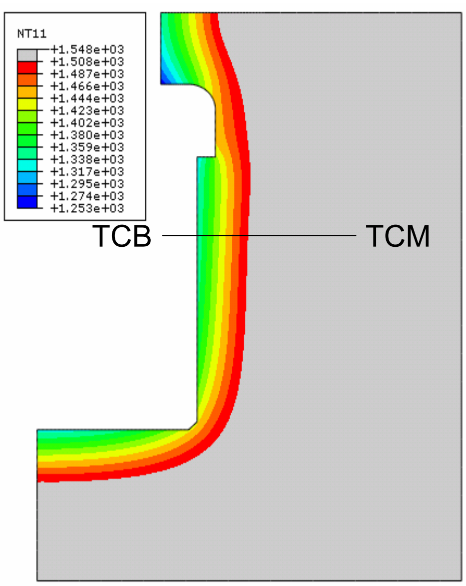
Temperature Histories





Shell Thickness

Steel 3, 24.6s

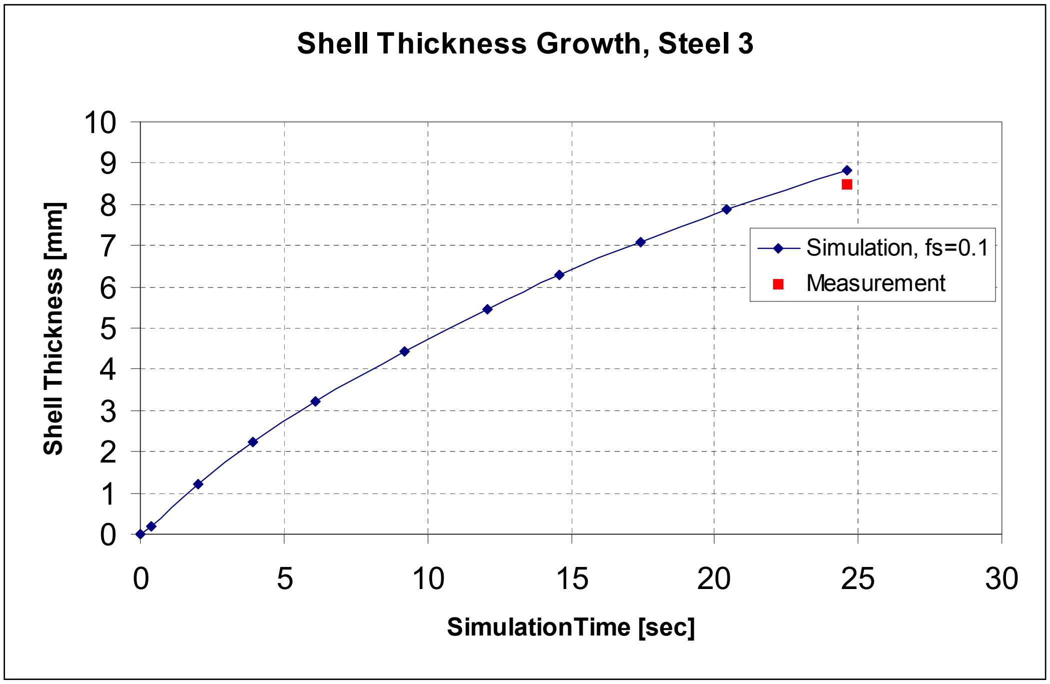


Determined from temperature profile
f_s=0.1

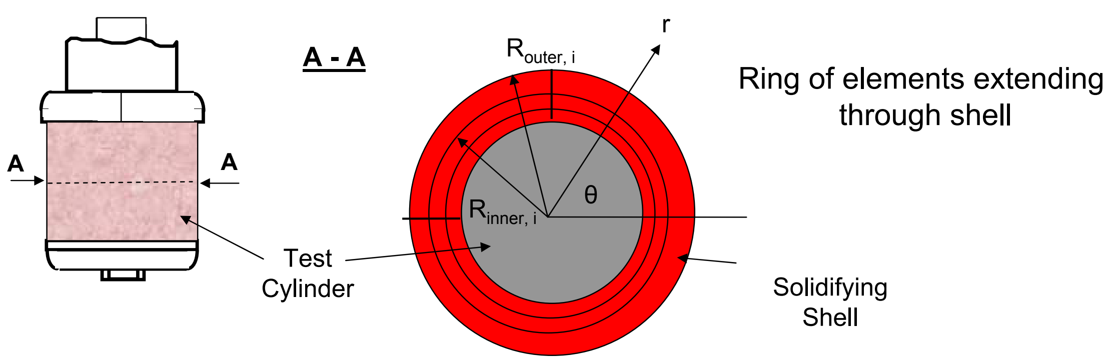
Thickness measured on same plane where thermocouples are located

Test #	Shell Thickness [mm] (Experimental)	Shell Thickness [mm] (Simulation)
1	8.8	8.56
2	8.76	9.1
3	8.5	**8.8**
4	10.14	8.8
5	8.9	7.1*
6	8.75	8.06*

Shell Growth Profile, Steel 3



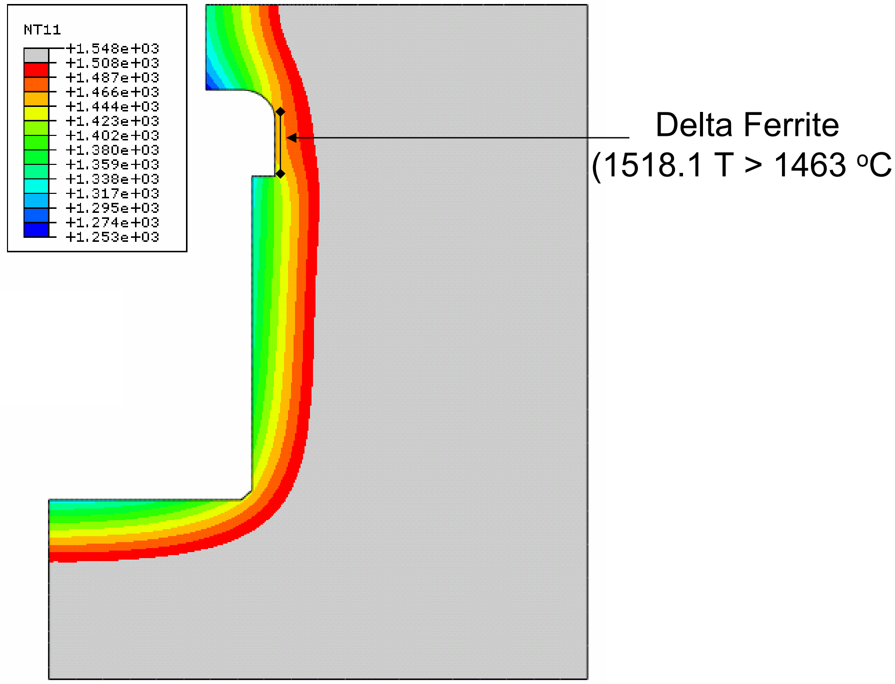
Force Determination – Shell



$$F = \int \sigma_y dA_{shell} \longrightarrow F = \sum_{elements} \int_{R_{inner,i}}^{R_{outer,i}} 2\pi\sigma_{y,i} r dr$$

$$F = \sum_{elements} \pi\sigma_{y,i}\left(R^2_{outer,i} - R^2_{inner,i}\right)$$

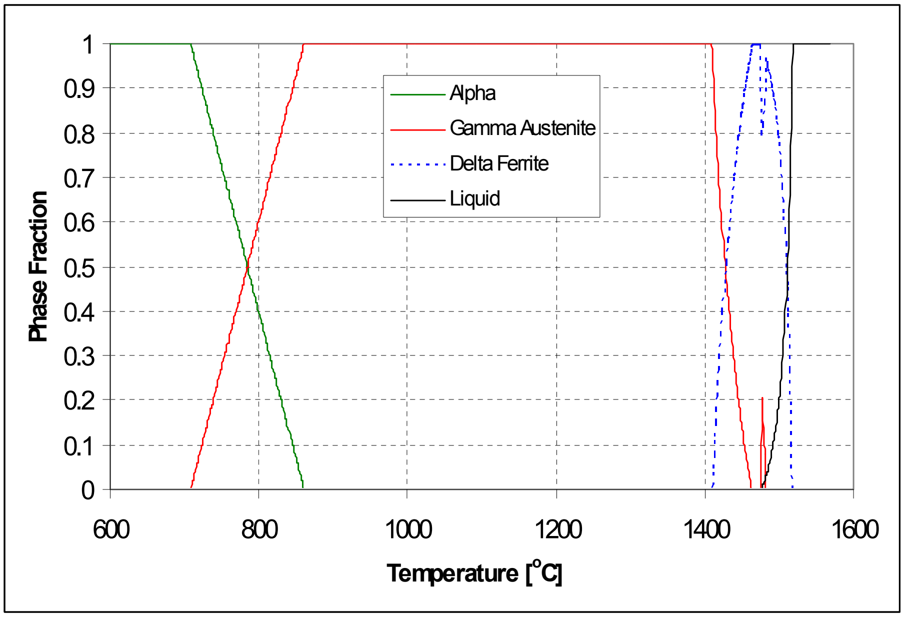
Axial Stress Distribution in Shell (Steel 3, t= 24.6 sec)



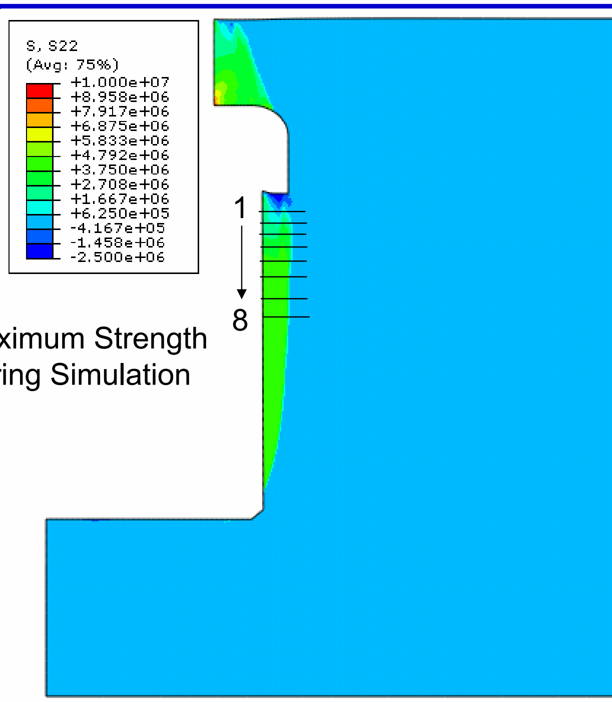
Shell Strength

- Different phases present across the shell thickness
- Increase in strength occurs during phase transformation of delta ferrite to austenite
- Location of maximum force in shell may change during solidification
  - Multiple locations investigated

Phase Fraction for 0.09% C Plain Carbon Steel

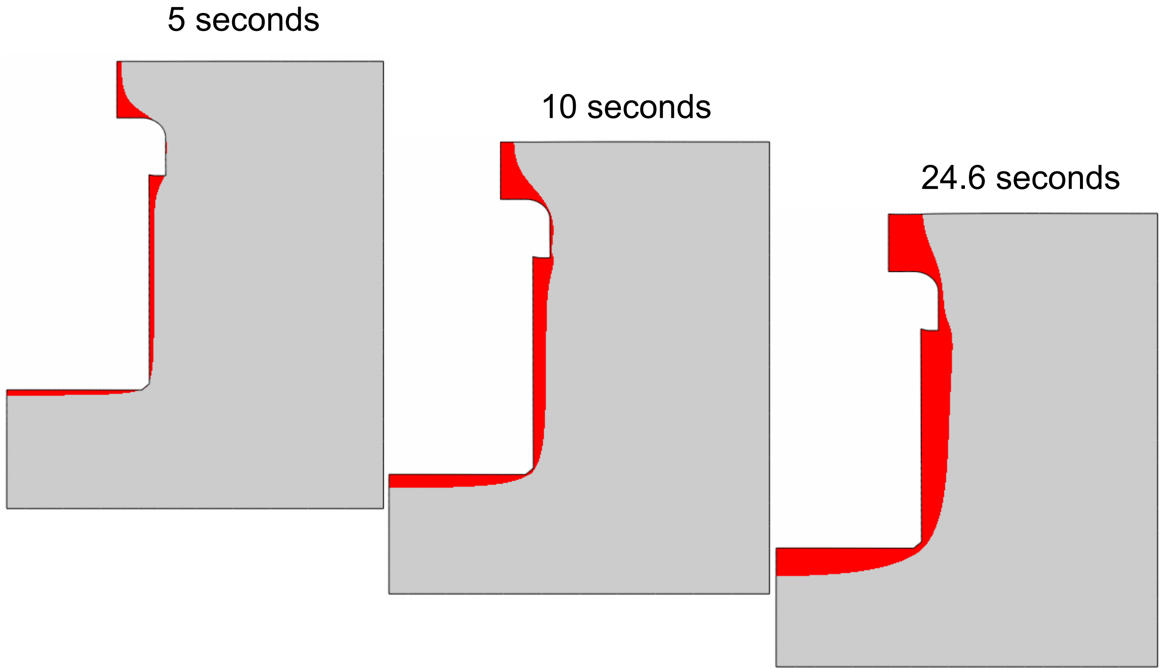


Axial Stress Distribution in Shell (Steel 3, t= 24.6 sec)



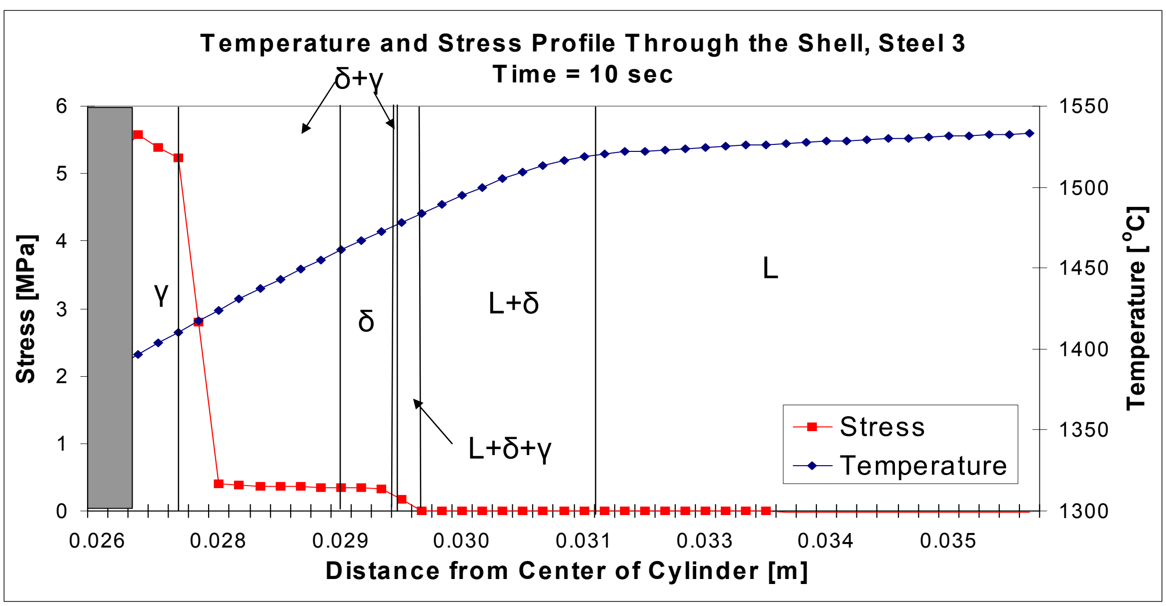
Location of Maximum Strength Changes During Simulation

Austenite Formation (Red)

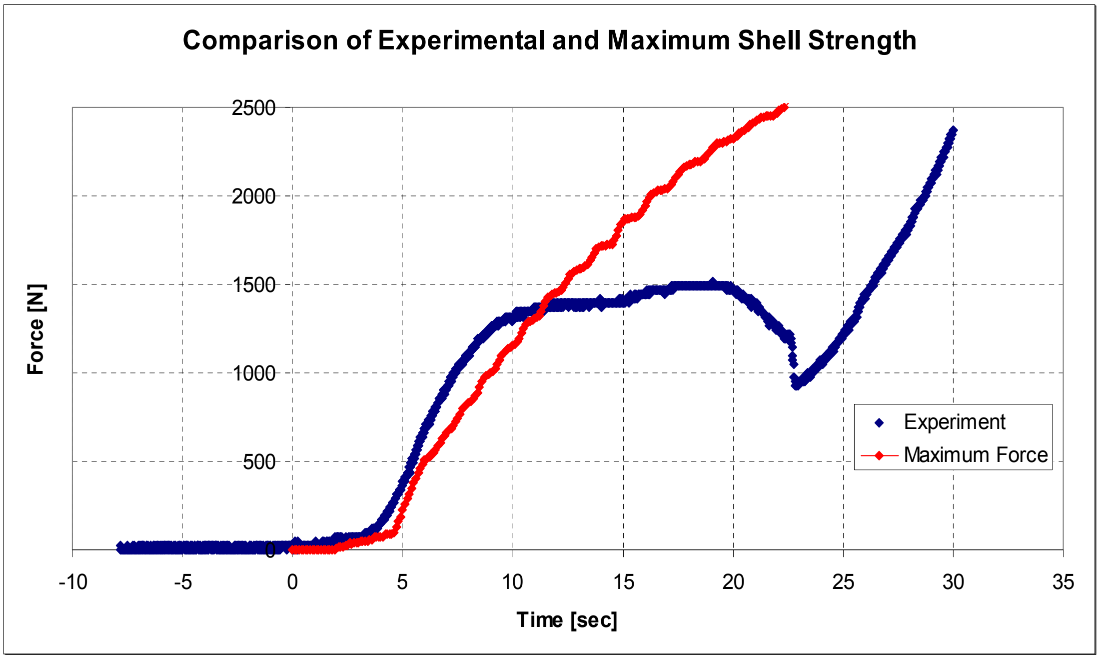


Phases Across Shell Thickness

Location 4



Shell Strength, Steel 3



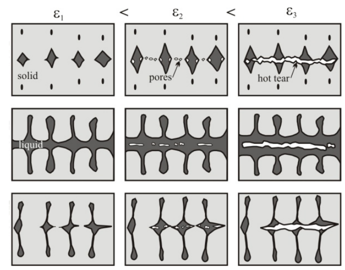
Shell Strength Analysis

- Maximum shell strength depends on:
  - Heat transfer
  - Temperature
  - Formation of austenite
- Thickest shell section is not the strongest

Hot Tearing Mechanisms

- **Breaking of solid-solid bridges (*Verö, 1936*)**
- **Liquid film rupture (*Pellini, 1952*)**
- **Liquid distribution between dendrites/grains (*Borland 1960*)**

- **Still basis of most hot tearing criteria**



- **Segregation is important to hot tearing in steel (*Bernhard, Pierer, 2007*)**
- **Modeling of HTS in CC process as segregation phenomenon**

#) P.-D. Grasso, J.-M. Drezet and M. Rappaz, January 2002 JOM-e: http://www.tms.org/pubs/journals/JOM/0201/Grasso/Grasso-0201.html

Hot Tear Crack Prediction

- Simulations do not take cracking into account
  - Cracking indicated by ‘plateau’ in force measurement data
- Time when simulation starts to deviate from experimental forces likely indicates start of crack formation

- To predict cracks: compare calculated and critical strain

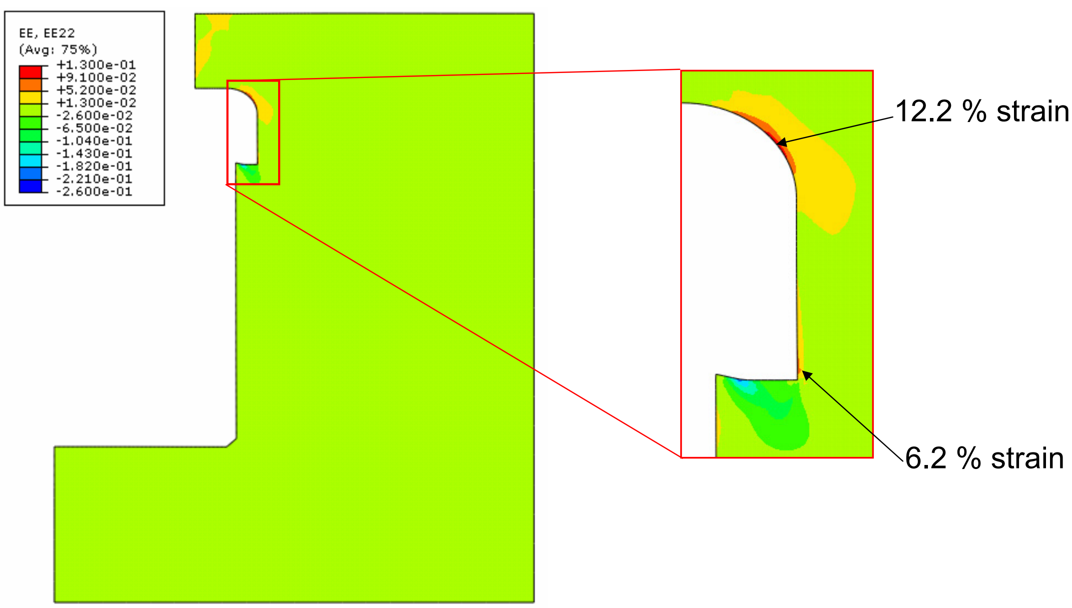
Calculation of Critical Strain

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

- 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

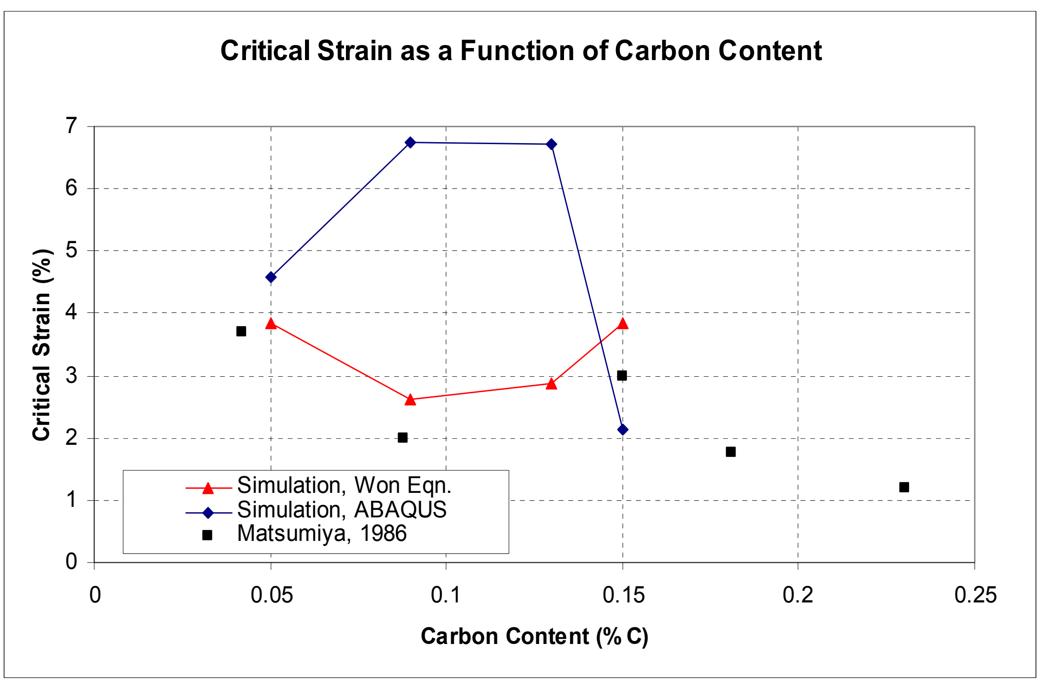
Inelastic Strain at Failure, t = 10 sec, Steel 3



Summary of Critical Strain Results

Steel #	T_{liq} (°C)	T_{sol} (°C)	$\Delta T_{brittle}$ (°C)	$\dot{\varepsilon}$ (1/sec)	ε_{crit}
1	1521.5	1493.99	9	8.6×10^{-4}	3.9
3	1518.08	1476.26	14	8.7×10^{-4}	2.6
4	1514.8	1470.16	12	9.4×10^{-4}	2.9
5	1513.47	1467.84	10	6.4×10^{-4}	3.9

Critical Strain as a Function of Carbon Content



Critical Strain Discussion

- Brittle Temperature Range
  - Determined from CON1D
- Inelastic Strains
  - High estimations
  - Constitutive model formulation
  - Enforcement of boundary condition
- Critical Strain
  - Better agreement with using Won formulation than using ABAQUS values for strain

Conclusions

- Model capable of predicting temperature profiles, shell thickness and forces and strains to failure for detailed case
  - Carbon content is an input variable
- Other steel cases:
  - Model needs improvement
    - Inelastic strain over-predicts critical strain
  - Empirical relation between critical strain and brittle temperature range
    - CON1D differs with published data

What We Need to Improve

- Need more certain values of experimental conditions
  - Pour Temperature (superheat)
    - Shell thickness
  - Experiment Duration
  - Initial temperature of test cylinder
    - Time between tests?
  - Multiple tests of one specific alloy to determine variance

Acknowledgements

- Continuous Casting Consortium Members
- Christian Bernhard & Robert Pierer
  - University of Leoben
- National Center for Supercomputing Applications (NCSA) at UIUC
- ABAQUS

Supplemental Material

Linear Gradient Across Zirconia Layer