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Grade Effects On The Initial Stress, Strain, And Solidification Behavior In Continuously Cast Steels

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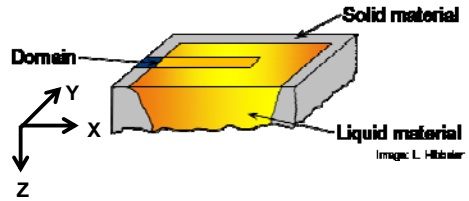
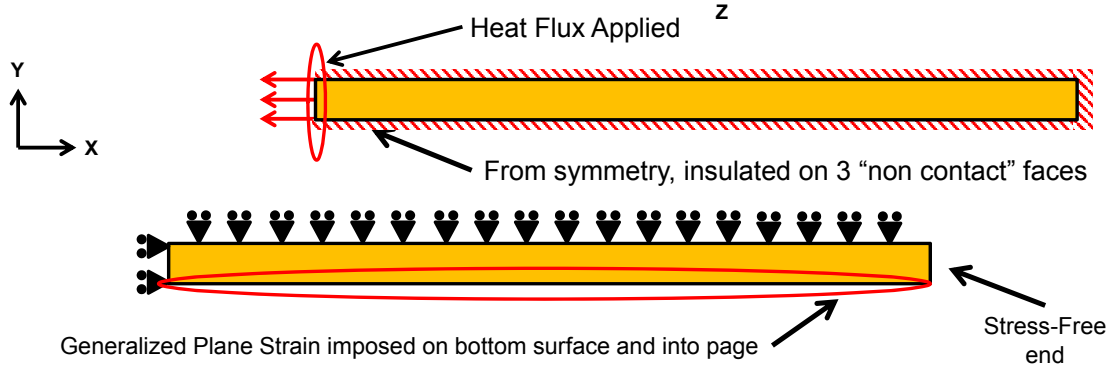
Problem Statement

The goal of this study is to explore the effect of steel grade on initial solidification using a "1D" free shrinking slice mode.

- **Free Shrinkage (No contact)**





Governing Equations

Heat Conduction Equation (with solidification):

$$\rho\left(\frac{\partial H(T)}{\partial T}\right)\left(\frac{\partial T}{\partial t}\right)=\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)$$

Equilibrium Equation (small strain assumption):

$$\nabla\cdot\boldsymbol{\sigma}(\mathbf{x})+\mathbf{b_o}=0$$

Rate Representation of Total Strain Decomposition:

$$\dot{\boldsymbol{\varepsilon}}=\dot{\boldsymbol{\varepsilon}}_{\mathrm{el}}+\dot{\boldsymbol{\varepsilon}}_{\mathrm{ie}}+\dot{\boldsymbol{\varepsilon}}_{\mathrm{th}}$$

Constitutive Law (Rate Form of elasticity eqs, No large rotations):

$$\dot{\boldsymbol{\sigma}}=\underline{\underline{\mathbf{D}}}:(\dot{\boldsymbol{\varepsilon}}-\dot{\boldsymbol{\varepsilon}}_{\mathrm{ie}}-\dot{\boldsymbol{\varepsilon}}_{\mathrm{th}})\qquad \underline{\underline{\mathbf{D}}}=2\mu\underline{\underline{\mathbf{I}}}+(\mathrm{k}-\frac{2}{3})\mathbf{I}\otimes\mathbf{I}$$

Inelastic (visco-plastic) Strain Rate (strain-rate-independent plasticity + creep):

$$\dot{\bar{\varepsilon}}_{\mathrm{ie}}=\mathrm{f}(\bar{\sigma},\mathrm{T},\bar{\varepsilon}_{\mathrm{ie}},\%C)=\sqrt{\frac{2}{3}\dot{\boldsymbol{\varepsilon}}_{\mathrm{ie}}:\dot{\boldsymbol{\varepsilon}}_{\mathrm{ie}}}\qquad \bar{\sigma}=\sqrt{\frac{3}{2}\boldsymbol{\sigma}':\boldsymbol{\sigma}'}\ ,\ \boldsymbol{\sigma}'=\boldsymbol{\sigma}-\frac{1}{3}\mathrm{trace}(\sigma)\mathbf{I}$$

Thermal Strain:

$$\{\varepsilon_{th}\}=(\alpha(T)(T-T_{ref})-\alpha(T_i)(\mathrm{T_i}-\mathrm{T_{ref}}))[111000]^T$$

Grades Of Interest

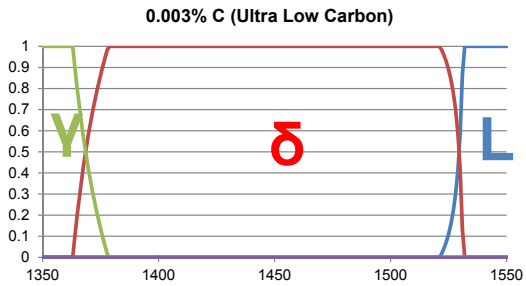
Element	Ultra Low [wt%]	Low [wt%]	Peritectic [wt%]	High [wt%]
Carbon	**0.003**	**0.040**	**0.130**	**0.470**
Aluminum	0.040	0.040	0.040	0.040
Chromium	0.010	0.010	0.010	0.010
Copper	0.010	0.010	0.010	0.010
Manganese	0.080	0.200	0.500	0.750
Nickel	0.010	0.010	0.010	0.010
Phosphorus	0.010	0.010	0.010	0.010
Sulphur	0.010	0.010	0.010	0.010
Silicon	0.005	0.020	0.015	0.220
Titanium	0.050	0.050	0.050	0.050
MidPlane Temp	**1540**	**1536**	**1527**	**1496**
Centerline Temp	**1534**	**1530**	**1521**	**1490**
Liquidus	1532	1528	1519	1488
Solidus	1521	1505	1479	1419
Mushy Zone	**11**	**23**	**40**	**69**
Gamma End	697	695	687	693
Alpha Start	885	868	826	743
Delta End/Solidus	1363	1385	1446	**1419**
Delta End/Solidus	1379	1419	**1479**	1478
Gamma Start/Solidus	**1521**	**1505**	1484	1482
Liquidus	1532	1528	1519	1488
70% Solidus	1481.3	1485.1	1497.1	1467.3

Solidus Temperature Indicated with Dark Grey

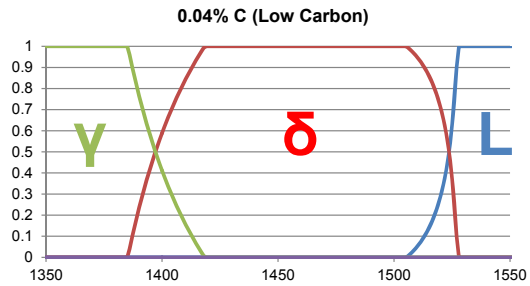
The Liquid is modeled as a Perfectly-Plastic Solid

- **Elastic Modulus:** 1E4 [MPa]
- **Poisson's Ratio:** 0.3 [mm/mm]
- **Yield Stress:** 1E-2 [MPa]

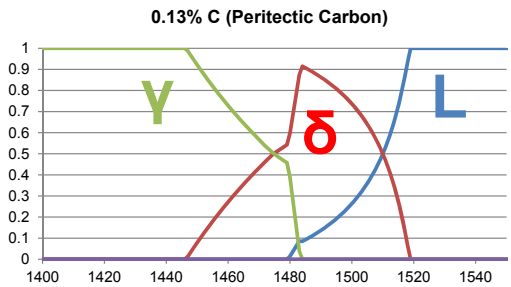
Grade Phase Fractions



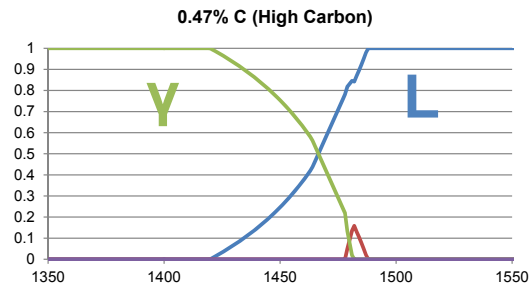
11 Degree Mushy



23 Degree Mushy



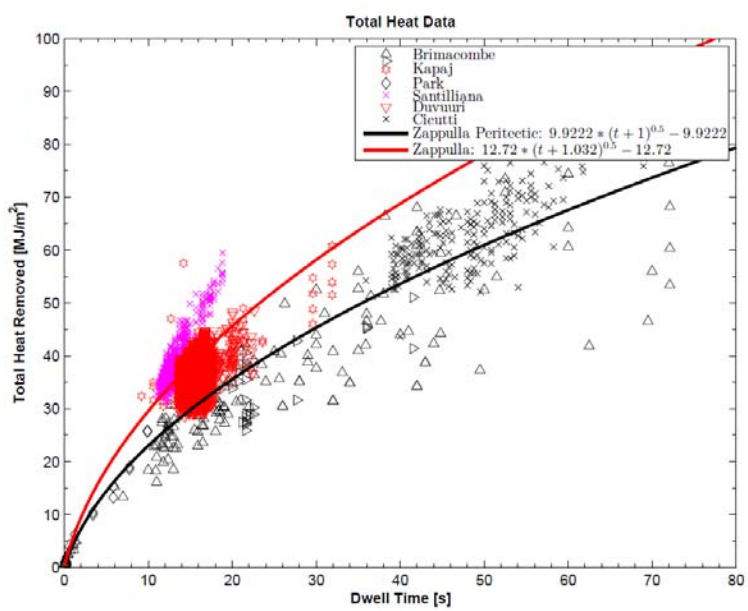
40 Degree Mushy



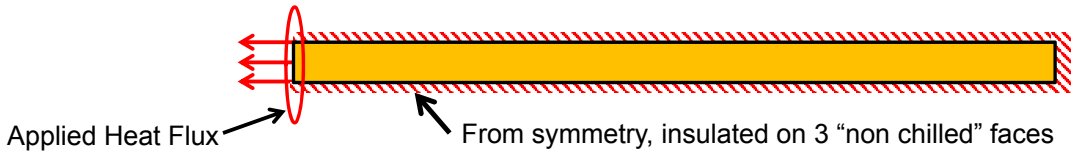
69 Degree Mushy

Heat Flux Data

- Collected and compiled from available data and the literature
- Regression curve fit for total heat flux data
- Avoid instabilities at zero
- Lower heat flux profile adopted for the Peritectic grade



Applied Heat Flux



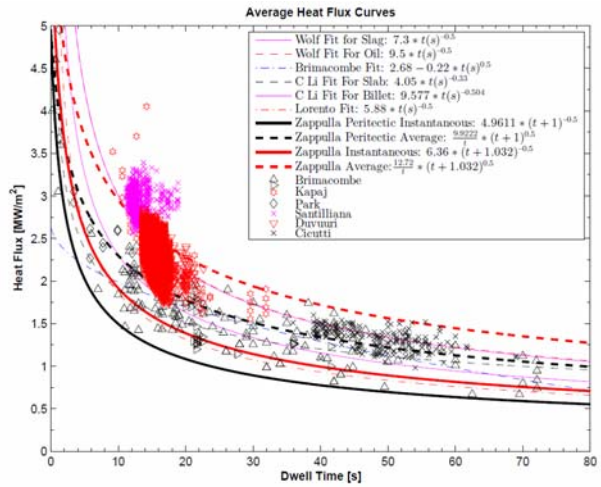
$$t_{Total} = Dwell\ Time$$

$$Q_{Average} = \frac{1}{t_{Total}} \int_0^{t_{Total}} \frac{Q_{Initial}}{\sqrt{(a+t)}} dt$$

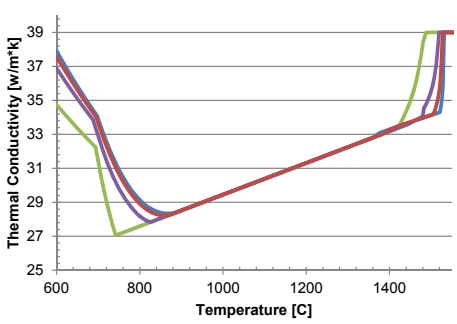
$$Q_{Initial} = \frac{Q_{Average} * t_{Total}}{2\sqrt{(a+t_{Total})}}$$

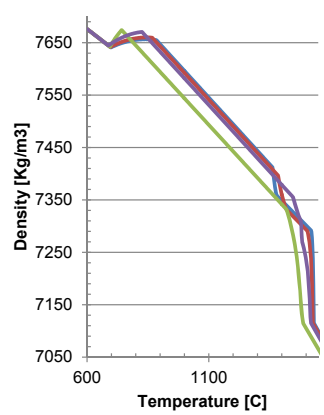
$$Heat\ Flux_{Instantaneous} = \frac{Q_{Inital}}{\sqrt{(a+t_{Total})}}$$

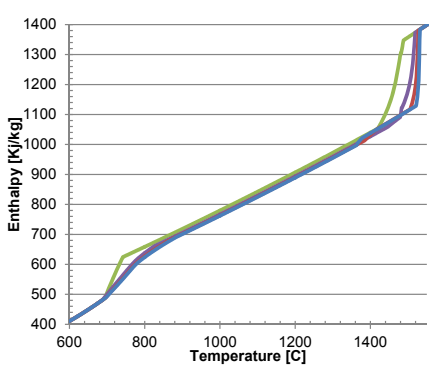
$$Peritectic\ Heat\ Flux_{Instantaneous} = \frac{Q_{Inital}}{\sqrt{(1+t_{Total})}}$$



Temperature & Grade Dependent Properties







Ultra Low Carbon

High Carbon

Low Carbon

Peritectic Carbon

Phase Fraction weighted average for all properties

$$\bar{\phi} = \phi_L f_L + \phi_\delta f_\delta + \phi_\gamma f_\gamma + \phi_\alpha f_\alpha$$

Thermal Conductivity

- K. Harste, Ph.D. Thesis, Technical University of Clausthal, (1989).

Enthalpy

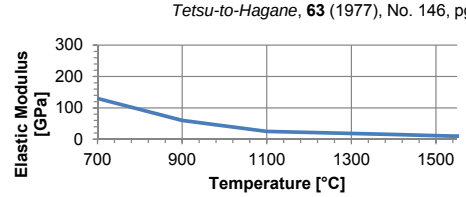
- K. Harste, Ph.D. Thesis, Technical University of Clausthal, (1989).

Thermal Expansion (from Density)

- K. Harste, Ph.D. Thesis, Technical University of Clausthal, (1989).
- I. Jimbo and A. Cramb, "The Density of Liquid Iron-Carbon Alloys." *Metallurgical and Materials Transactions*, **24B** (1993), No. 1, pg. 5-10.

Elastic Modulus

- H. Mizukami, K. Murakami, and Y. Miyashita, "Elastic Modulus of Steels at High Temperature." *Tetsu-to-Hagane*, **63** (1977), No. 146, pg. S652.



Constitutive Equations

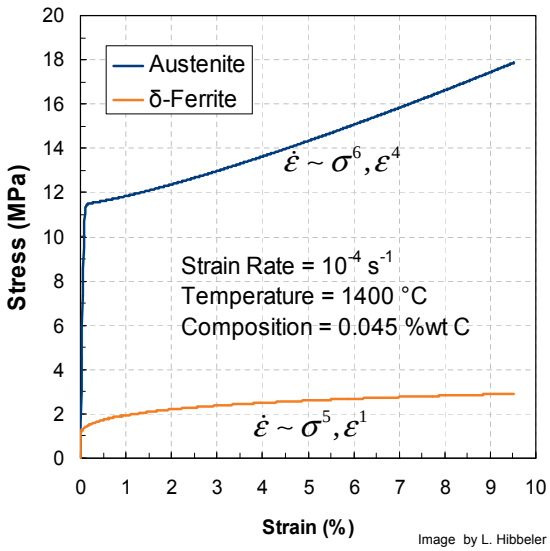


Image by L. Hibbeler

- P.F. Kozlowski, B.G. Thomas, J.A. Azzi, and H. Wang, "Simple Constitutive Equations for Steel at High Temperature." *Metallurgical and Materials Transactions*, **23A** (1992), No. 3, pg. 903-918.
- H. Zhu, "Coupled Thermo-Mechanical Finite-Element Model with Application to Initial Solidification." Ph.D. Thesis, University of Illinois at Urbana-Champaign, (1996).

- Austenite (Kozlowski model III):

$$\dot{\varepsilon}\left(s^{-1}\right) = f(C)\left[\sigma - f_1(T)\varepsilon\left|\varepsilon\right|^{f_2(T)-1}\right]^{f_3(T)} \exp\left(-\frac{4.465\times10^4(K)}{T}\right)$$

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

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

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

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

- δ-ferrite (Zhu modified power law):

$$\dot{\varepsilon}\left(s^{-1}\right) = 0.1\left|\sigma / f(C)(T/300)^{-5.52}(1+1000\varepsilon)^m\right|^n$$

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

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

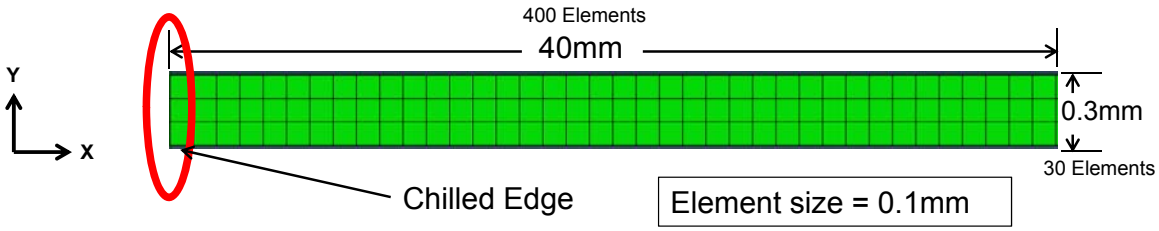
$$n = 1/1.617\times10^{-4}T - 0.06166$$

Liquid modeled as a Perfectly-Plastic Solid

- **Elastic Modulus:** 1E4 [MPa]
- **Poisson's Ratio:** 0.3 [mm/mm]
- **Yield Stress:** 1E-2 [MPa]

T in Kelvin, σ in MPa, C in weight % C

ABAQUS Mesh Implementation



Steel Shell Slice Model

- CPEG4HRT Elements
  - Two dimensional
  - Piecewise Linear
  - Continuum Stress/Displacement (C)
  - Generalized Plane Strain (PEG)
  - 4 nodes
  - Reduced (R)
  - Hybrid (H)
  - <u>One-Way</u> Coupled Temperature Displacement (T)
    - Stress Calculation has NO effect on Thermal Calculation

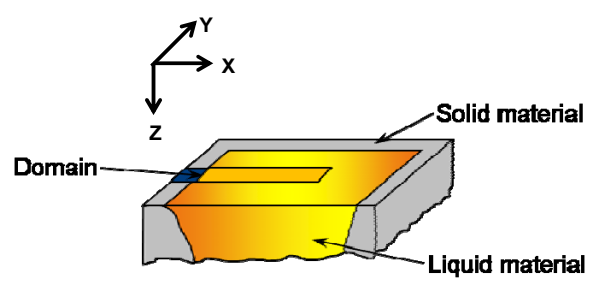
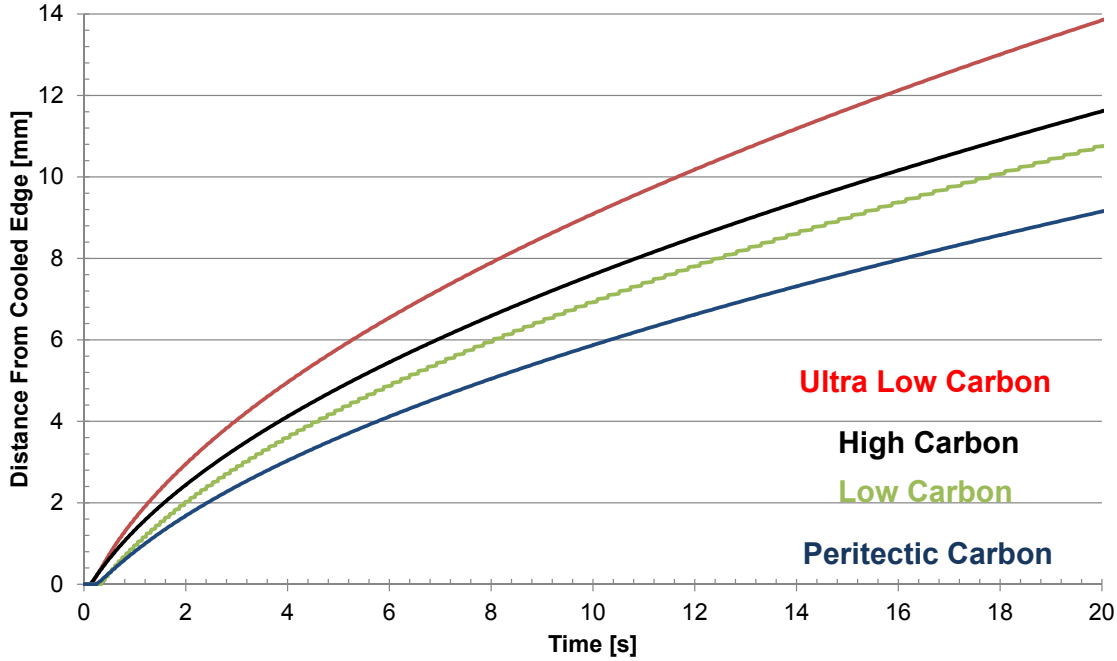
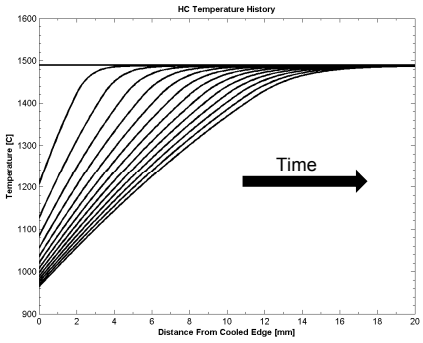


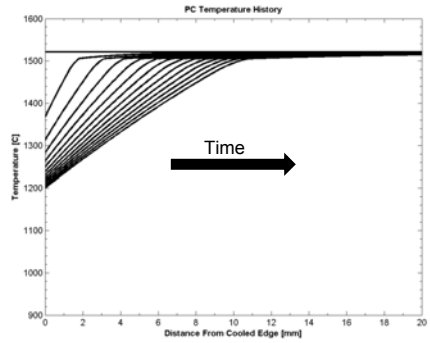
Image: L. Hibbeler

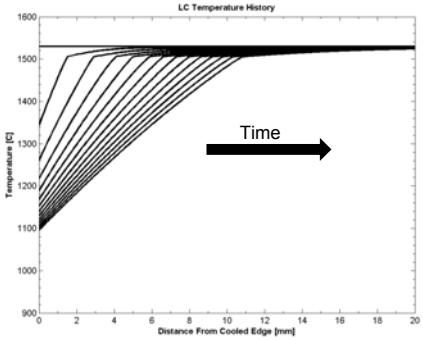
Shell Thickness - Solidus

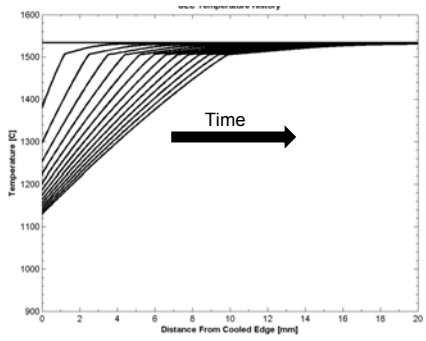


Temperature Histories

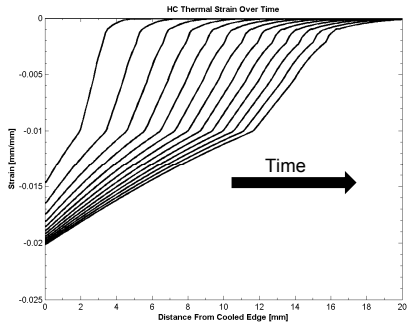


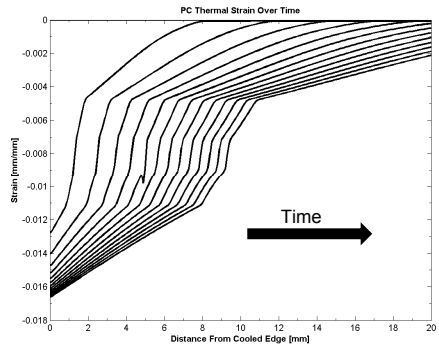


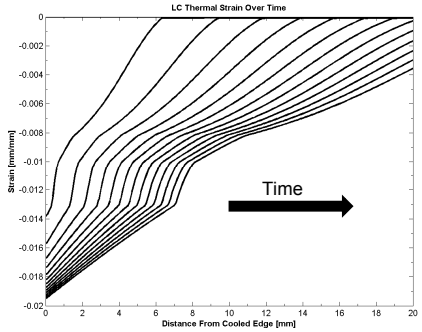


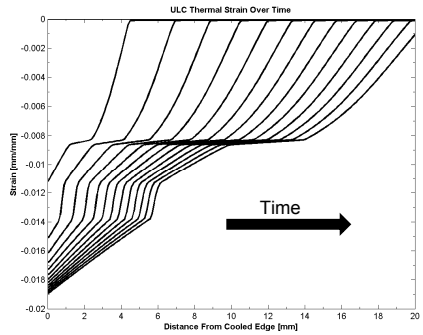


Thermal Strain Behavior

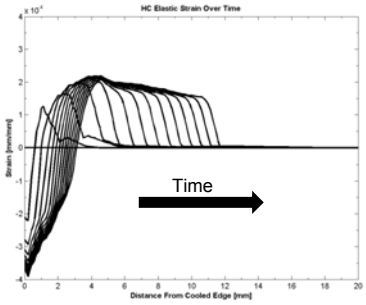


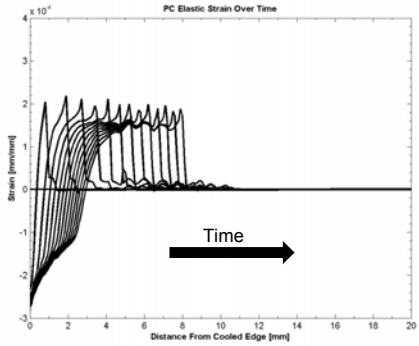


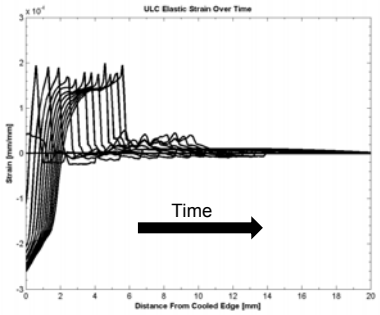


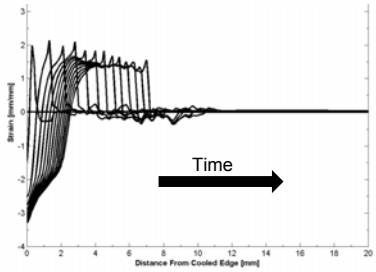


Elastic Strain Behavior

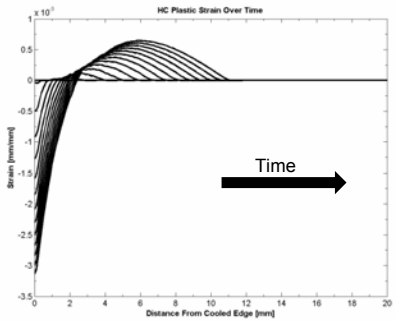


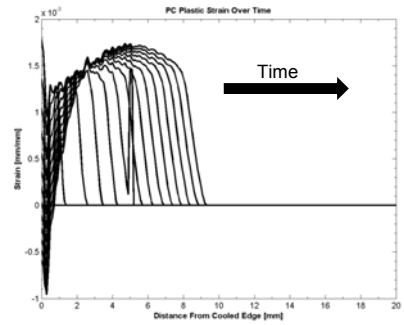


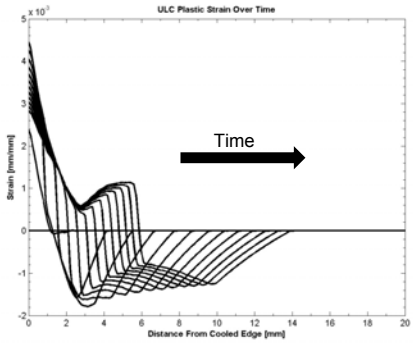


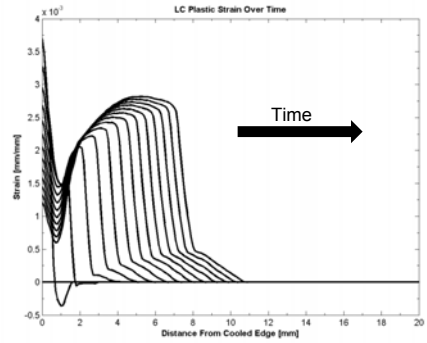


Plastic Strain Behavior

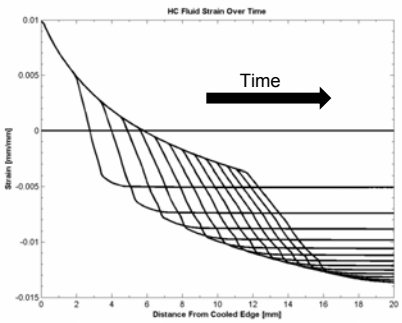


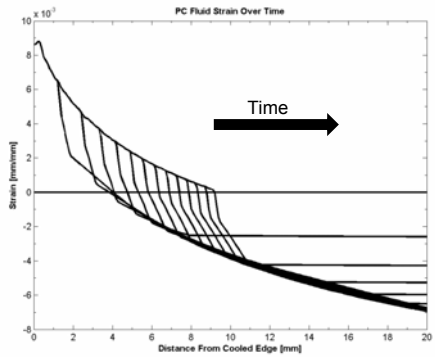


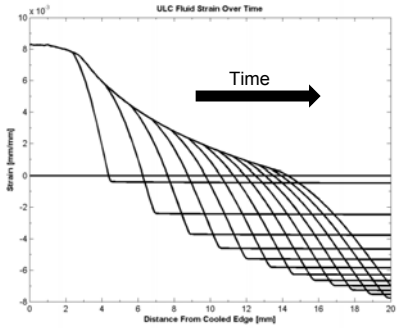


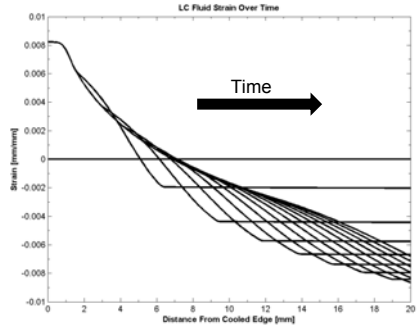


Fluid Strain Behavior

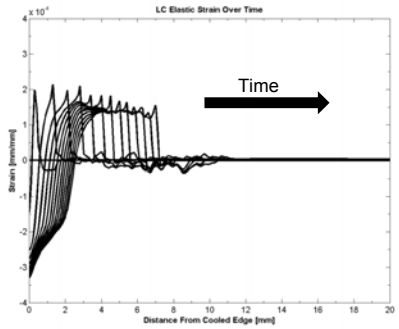


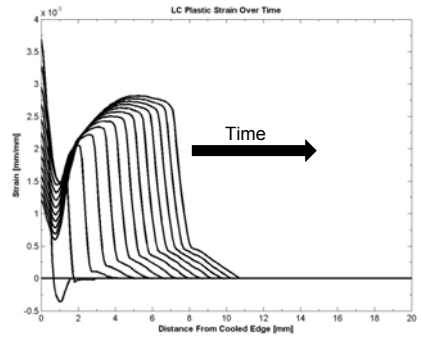


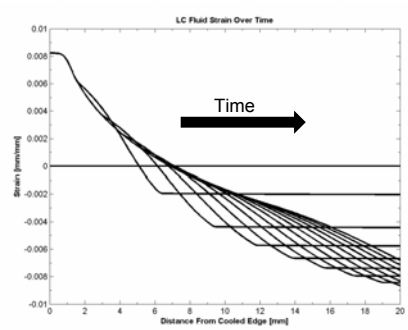


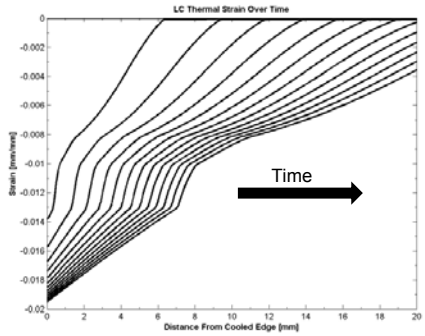


Low Carbon Strain Behavior

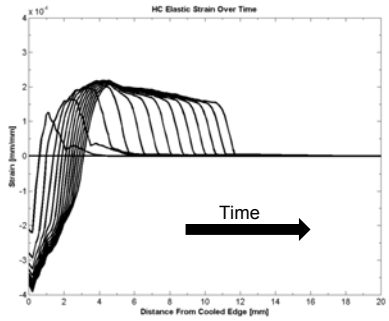


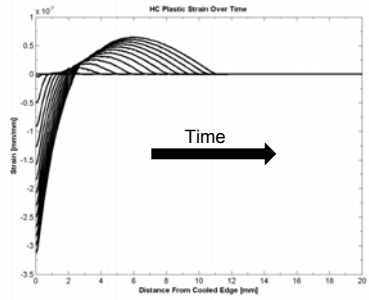


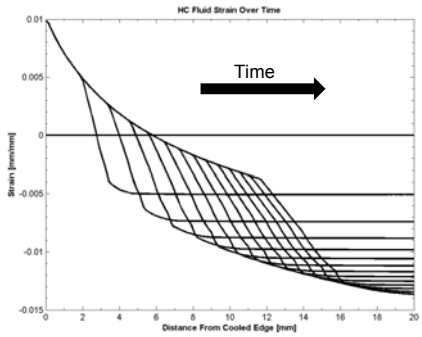


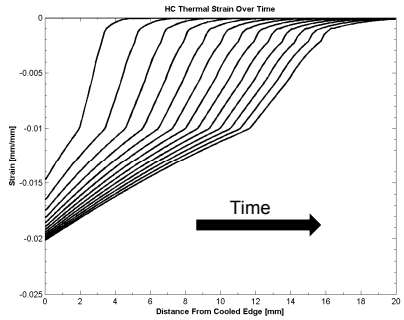


High Carbon Strain Behavior

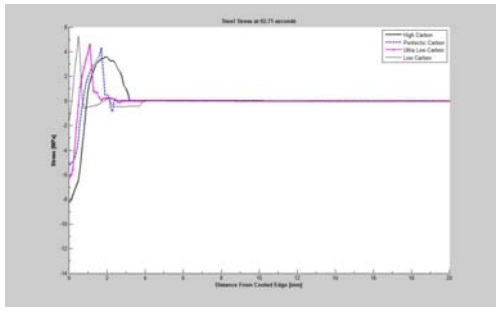


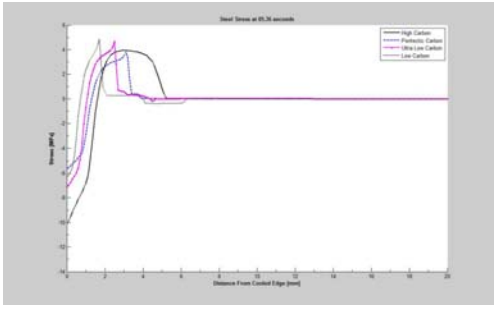


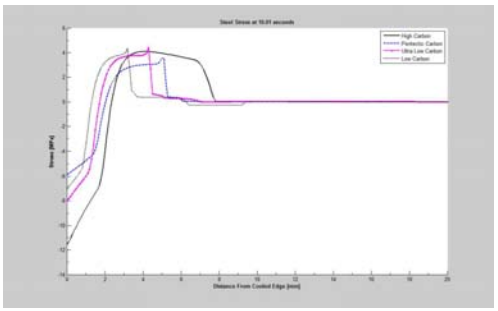


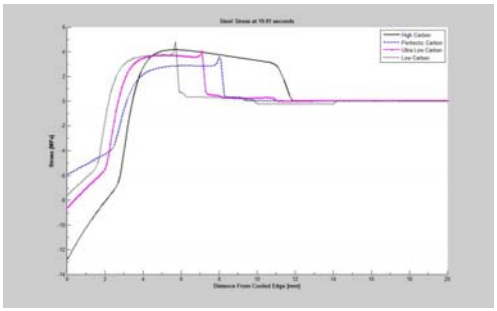


Stress Perpendicular to Solidification Front

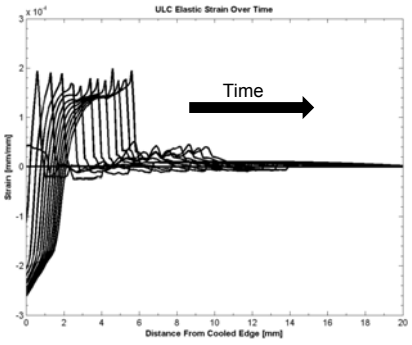


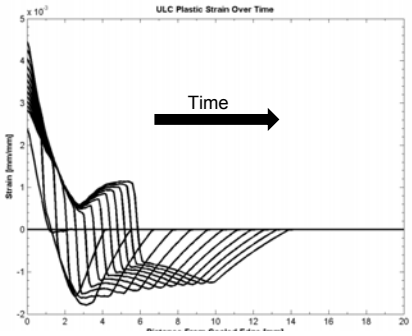


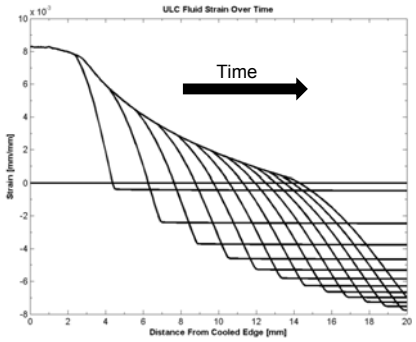


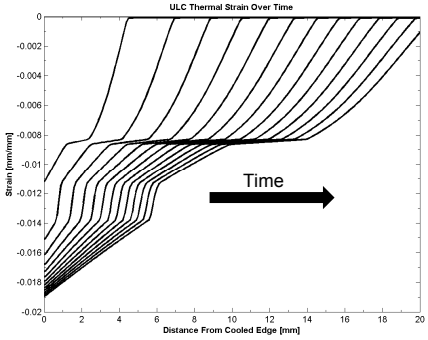


Ultra Low Carbon Strain Behavior

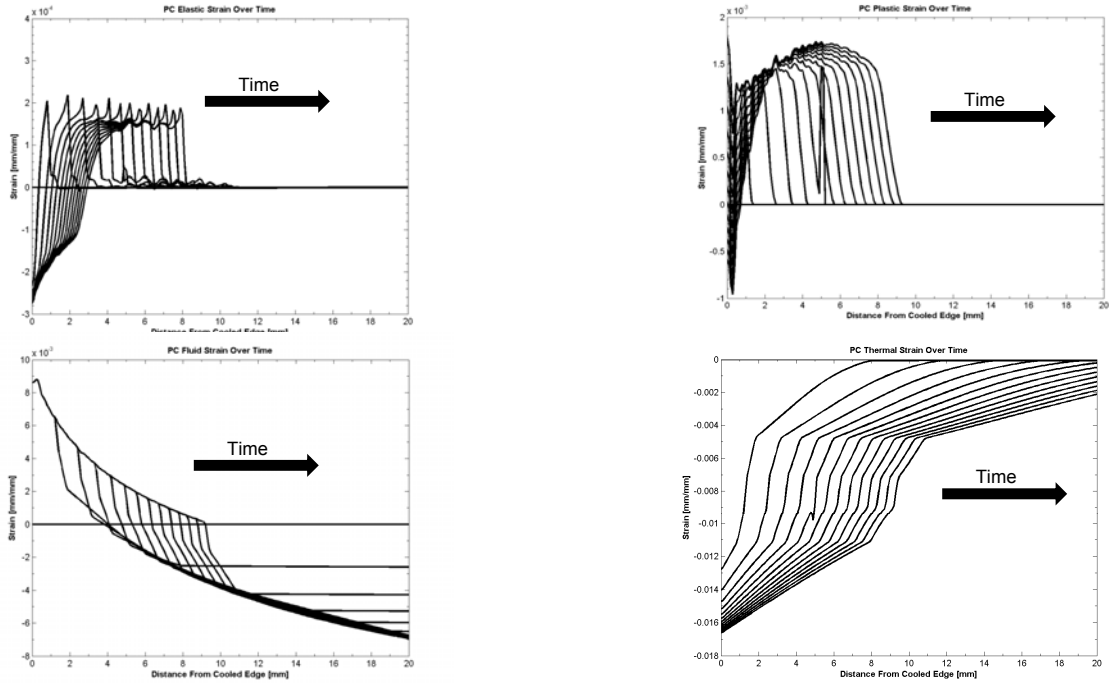








Peritectic Carbon Strain Behavior



Conclusions

- Free shrinkage of a 1D continuous casting slice with varying grades was modeled
  - Stress analysis reveals behavior of compression at the surface moving towards tension at the solidification front
  - Uniform total strain
  - Increasingly negative total strain was observed with time
  - Strain first increases (squeezed by shrinking solid) then later decreases (liquid shrinkage)
  - An initial period of negative plastic strain development that does not persist
    - Not seen in the High Carbon Grade, due to the absence of delta ferrite

Future Work

- Further development of an all encompassing model
- More grade accuracy by updating the phase diagram model

Acknowledgements

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