CCC Annual Report

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Thermo mechanical Analysis of Solidifying Shell Including Bending and Unbending

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Executive Summary

- This work investigates the effects of bending, unbending, and spray cooling on the mechanical behavior of a solidifying steel shell.

The new model quantifies:

- Cyclic stress-strain behavior in the steel shell during spray cooling.
- Transverse crack susceptibility at the inner radius surface during unbending via fatigue.

Introduction

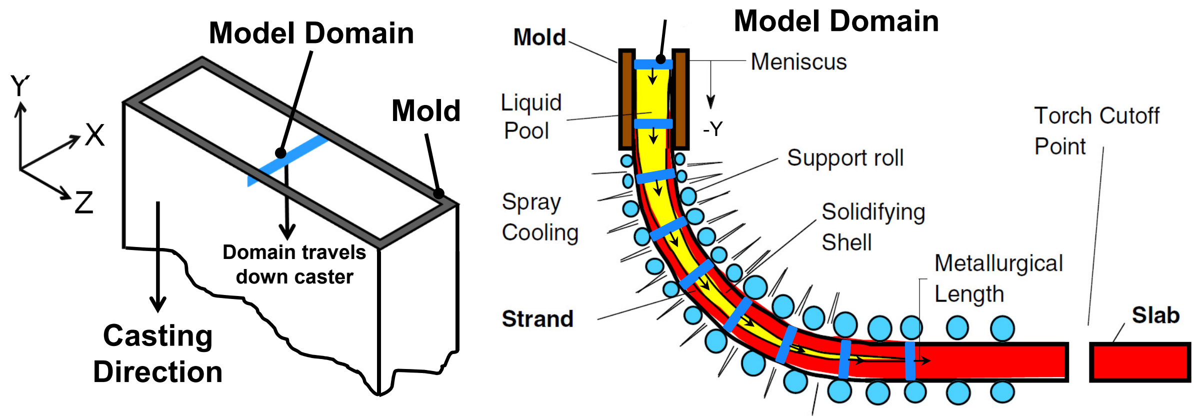
- During continuous casting the steel shell is subjected to thermal cycling in the spray cooling zone and bending/unbending stresses.
- Thermal cycling, bending and unbending contribute to the formation of transverse cracks.
- The thermo mechanical behavior of the solidifying steel strand in spray cooling should be investigated.

Modeling Objective

- The objective of this model was to determine the mechanical behavior through the solidifying steel strand with a narrow slice due to mold, spray cooling, bending and unbending.
- The mechanical behavior of the shell from meniscus to caster exit can then be used to understand formation of transverse cracks.
- This model will later be modified to include microstructural features of columnar austenite grains with grain-boundary ferrite and/or precipitates.

- All experiments were run on ABAQUS/Standard 6.13.2 on Windows 7.

Model Domain



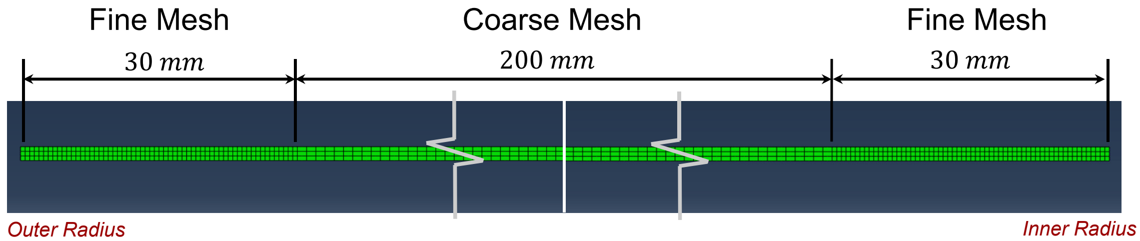
Caster image from ccc.illinois.edu

- Model domain centered at wide face and extends through the slab.
- Model domain travels axially at casting speed through the mold and spray cooling zones.

Modeling Steps

1. CON1D is used to calculate thermal boundary conditions at shell surface.
2. Thermal Abaqus model is used to calculate the temperature field in the domain.
3. Mechanical Abaqus model uses this temperature field to drive the mechanical response of domain.

Mesh Properties

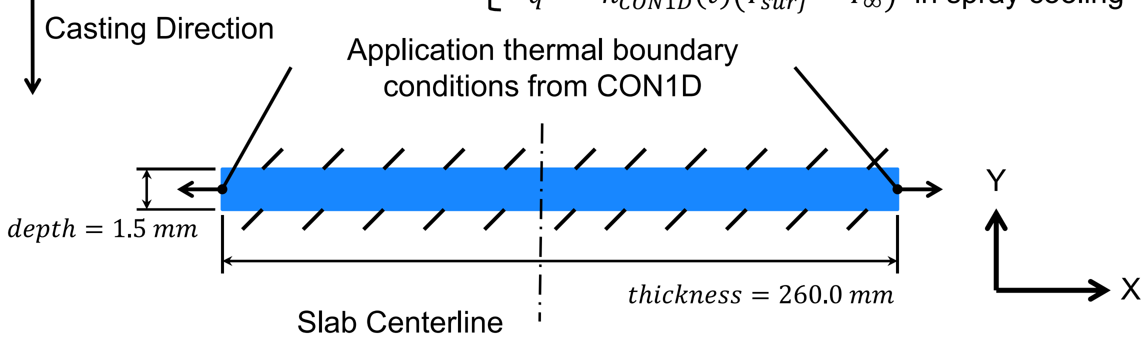


- Thermal Element Type:
  - DC2D8: 8 node biquadratic quadrilateral diffusive heat transfer.
  - Fully integrated with 3x3 Gauss-Legendre integration.
- Mechanical Element Type:
  - CPEG8H: 8 node biquadratic quadrilateral, hybrid with linear pressure. Generalized plane strain.
  - Fully integrated with 3x3 Gauss-Legendre integration.
- Mesh Dimensions:
  - Total Domain Size: 260 mm x 1.5 mm
  - Fine Element Size: 0.5 mm x 0.5 mm
  - Coarse Element Size: 1.0 mm x 0.5 mm
  - Total of 960 elements
  - Total of 3,534 nodes
  - Fine elements extend from shell surface to 30 mm below shell surface

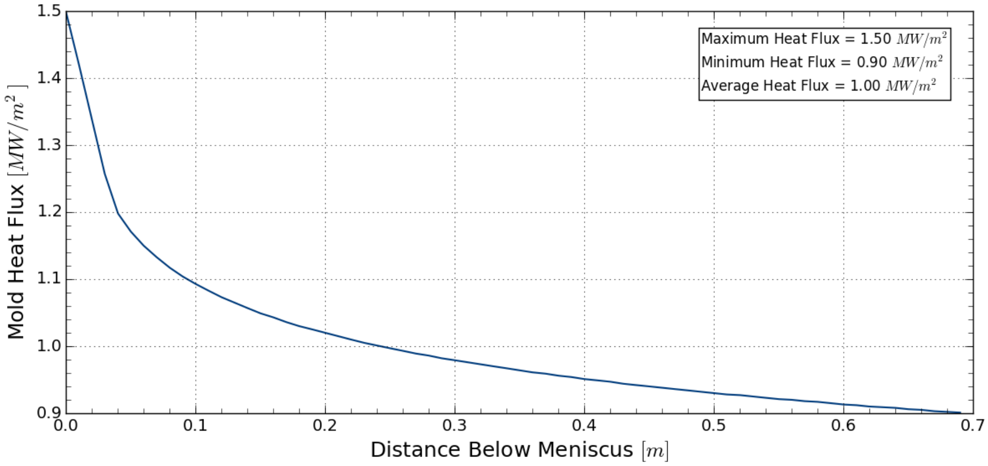
Thermal Boundary Conditions

- Thermal boundary conditions correlating to steel slab surface are applied at shell surfaces. Heat flux is assumed to be uniform at the surface of the domain.
- All other faces are insulated.
- Heat flux boundary conditions are imposed on the shell surface according to calculations from CON1D to simulate heat transfer in the mold.
- Convective film boundary conditions are imposed on shell surface according to calculations from CON1D to simulate heat transfer in the spray cooling zone.

$$q''(t) = \begin{cases} q'' = q''_{CON1D}(t) & \text{in mold} \\ q'' = h_{CON1D}(t)\left(T_{surf} - T_\infty\right) & \text{in spray cooling} \end{cases}$$

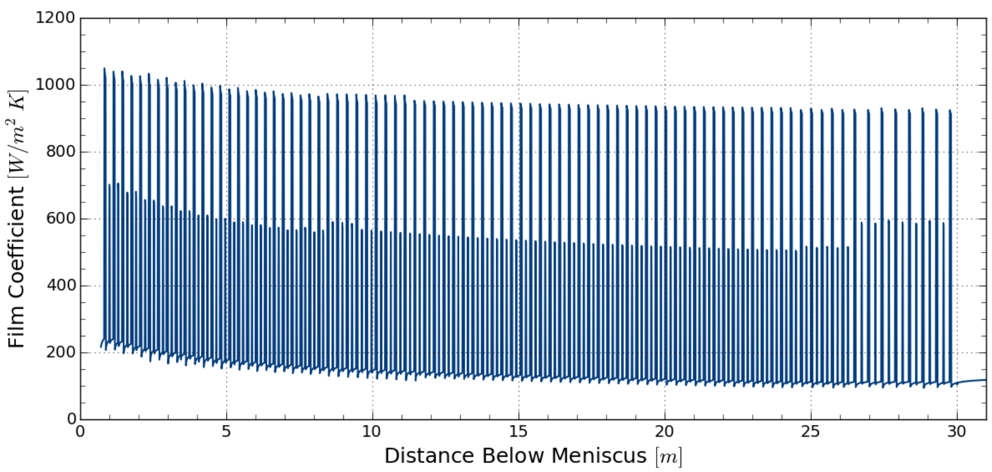


Thermal Boundary Conditions in the Mold



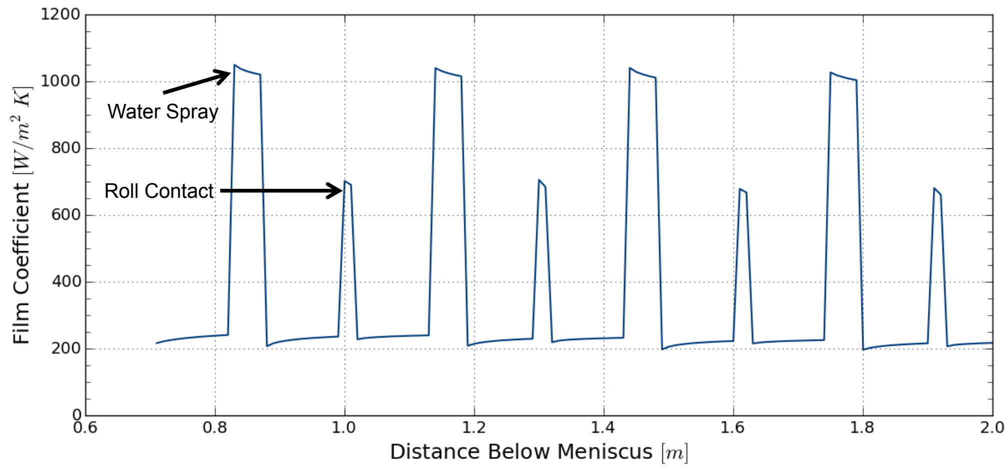
- Heat flux versus distance below meniscus, from CON1D. This heat flux data was used as a boundary condition for the Abaqus domain when it was in the mold.

Thermal Boundary Conditions in Spray Cooling Zone



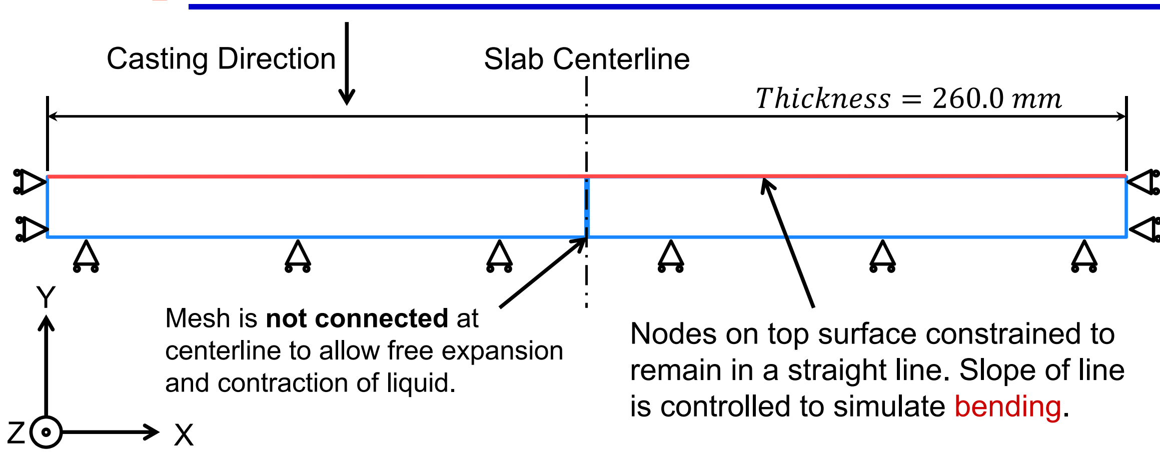
- Film coefficient versus distance below meniscus data from CON1D. This data was used to simulate the spray cooling zone. The spray water temperature was 25°C.
- Total of 86 roll contact zones and 87 water spray zones.

Thermal Boundary Conditions in Spray Cooling Zone



- Zoomed view of the film coefficient on the shell surface versus the shell's distance below the meniscus. The effects of spray cooling and roll contact are indicated.

Mechanical Boundary Conditions



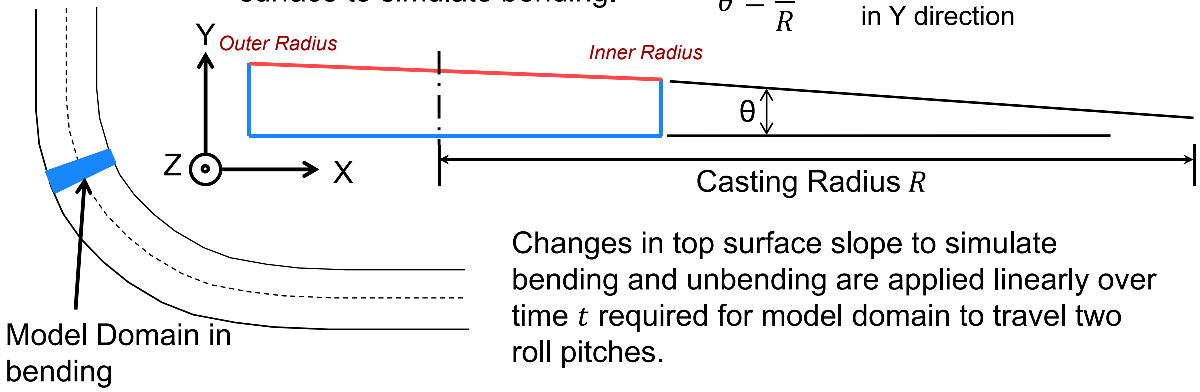
- Strand thickness is in X-direction – machine taper = 0.
- Strand length is in Y-direction – bending and unbending is controlled by rotating top surface.
- Strand width is in Z-direction - modeled using generalized plane strain elements.

Bending Boundary Conditions

Slope $m = tan(\theta)$ applied to top surface to simulate bending.

$$\theta = \frac{d}{R}$$

d = Initial domain size in Y direction

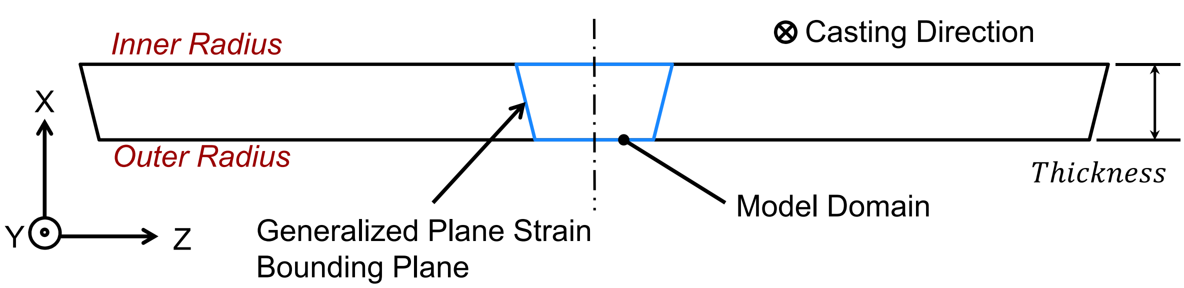


Changes in top surface slope to simulate bending and unbending are applied linearly over time t required for model domain to travel two roll pitches.

- Bending Assumptions:
  - The domain depth in Y-direction does not change significantly during solidification.
  - X displacements at the shell surfaces due to bending are negligible. (74 nm)
  - Plane sections remain plane during bending.

Width Direction Boundary Conditions

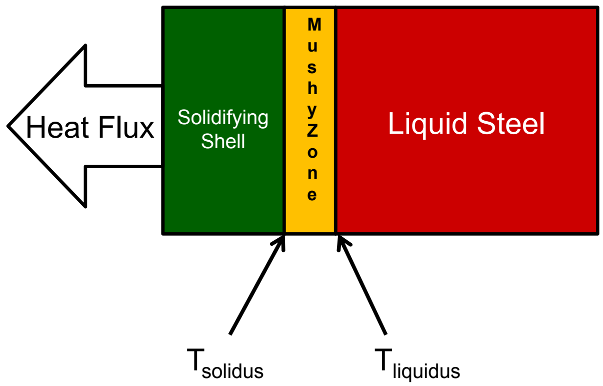
- Generalized Plane Strain Elements: $\varepsilon_{zz} = a + bx$



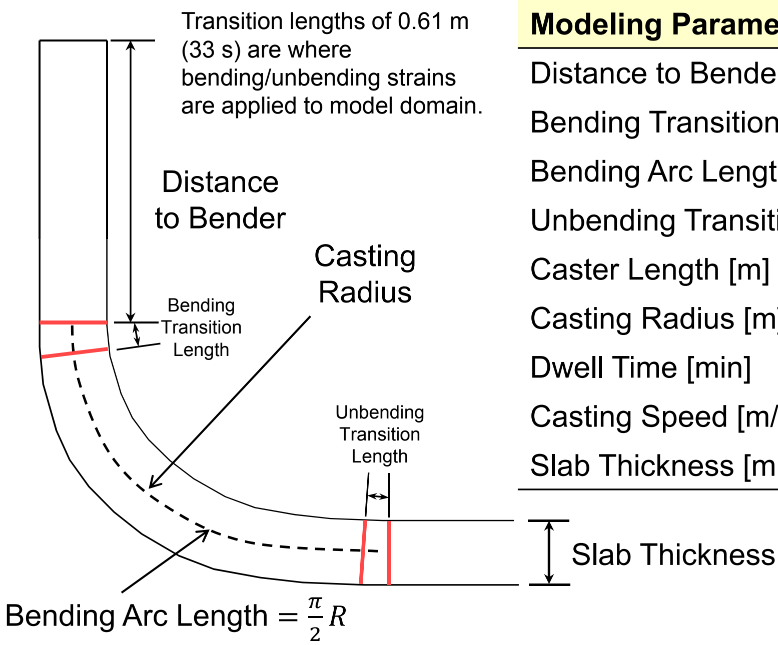
- Generalized plane strain elements are modeled having a Z-direction thickness determined by a bounding plane.
- The generalized plane strain bounding plane for all elements is allowed to rotate about the Y axis, allowing for linear variations in the Z-strain in the X direction.
- The bounding plane is constrained against rotation about the X axis.

Thermal Simulation Conditions

Model Parameter	Value
Initial Temperature [°C]	1550
Superheat [°C]	22
$T_{liquidus}$ [°C]	1528
$T_{solidus}$ [°C]	1508
T_{sink} for Spray Water [°C]	25
Mold Length [m]	0.690
SSC Zone Length [m]	30.291
Slab Thickness [m]	0.260

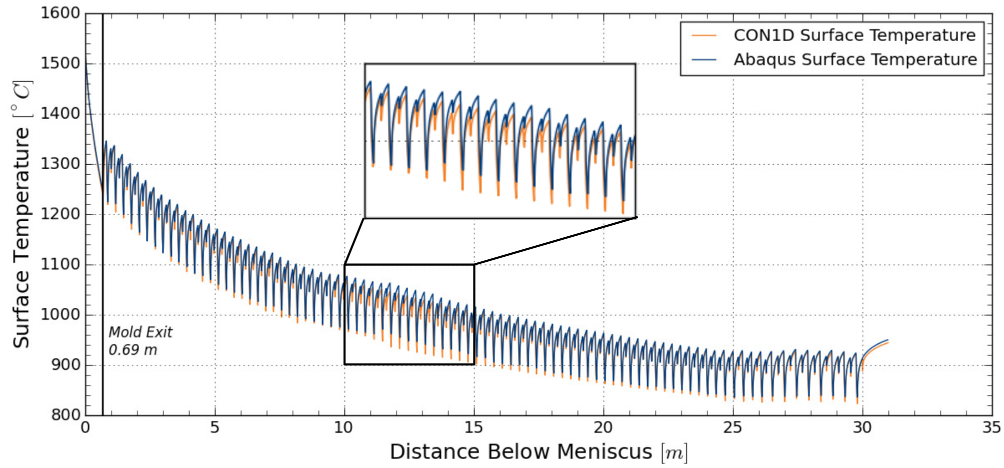


Mechanical Simulation Conditions



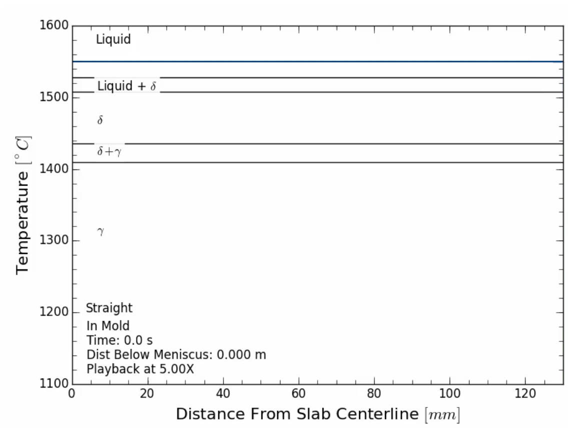
Modeling Parameter	Value
Distance to Bender [m]	2.83
Bending Transition Length [m]	0.61
Bending Arc Length [m]	23.56
Unbending Transition Length [m]	0.61
Caster Length [m]	31.0
Casting Radius [m]	15.0
Dwell Time [min]	28.2
Casting Speed [m/min]	1.10
Slab Thickness [mm]	260.0

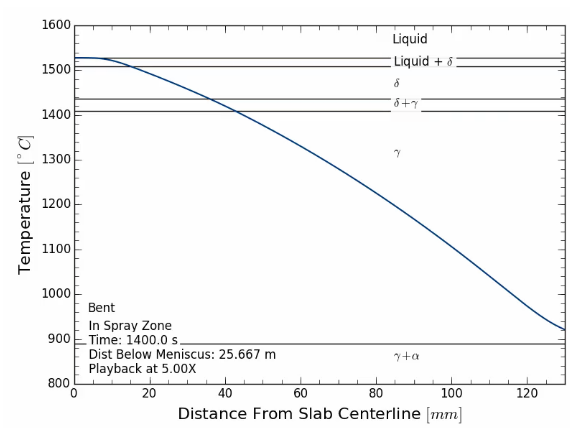
Surface Temperature Comparison



- Comparison of shell surface temperatures from CON1D simulation and Abaqus simulation.
- The average surface temperature difference is 7.22°C.

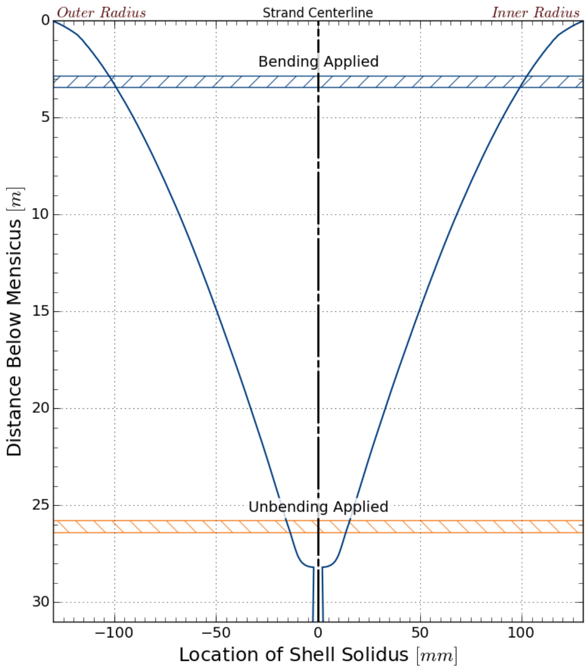
Temperature Results





- Plots showing the temperature through the thickness of the shell as a function of distance below meniscus.
- Note the oscillation of the shell surface temperature above and below the γ→ γ+α transition temperature.

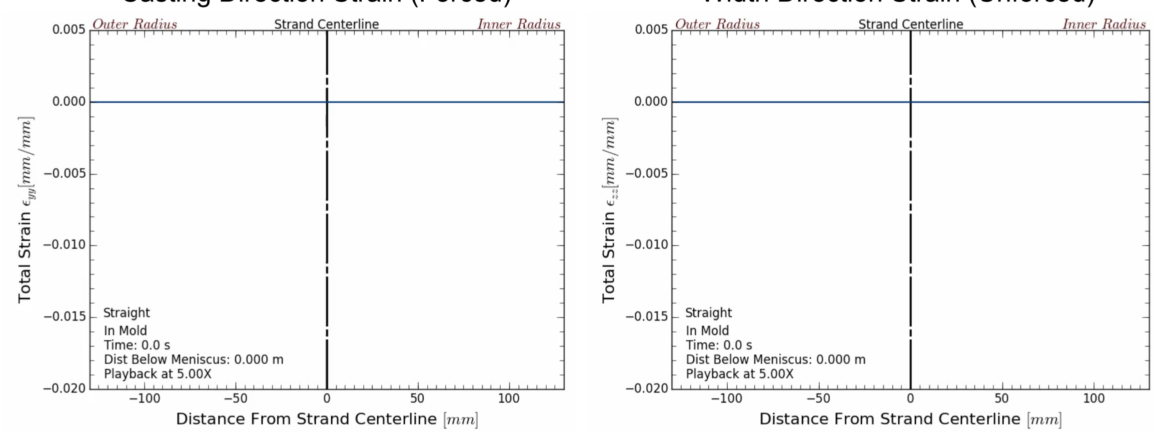
Shell Thickness Profile



- Hot tears and subsurface cracking could occur at 27 mm below the outer radius surface during bending.
- Subsurface cracking could occur 105 mm below the inner radius surface during unbending.
- The metallurgical length is ~28.0 m.
- The shell solidus does not connect at the metallurgical length because of domain shrinkage.

Total Strain in Bending

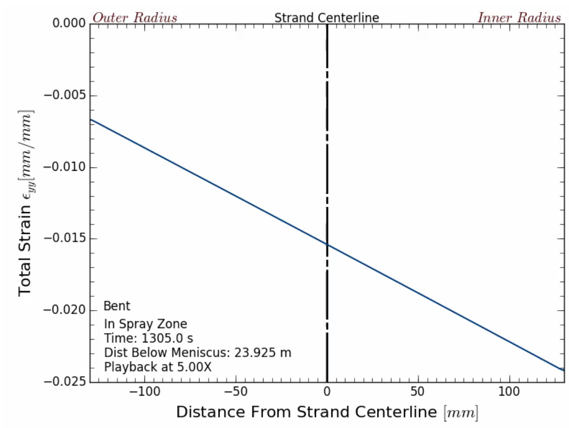
Casting Direction Strain (Forced)   Width Direction Strain (Unforced)



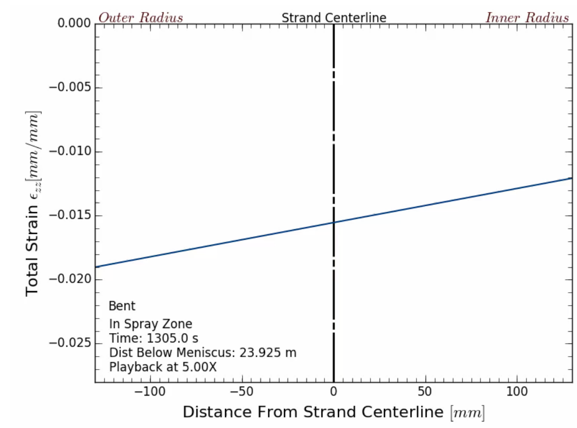
- The total strain in the casting direction (Y) is linear through the thickness, being compressed at the inner radius and stretched at the outer radius.
- The total strain in the width direction (Z) is linear, expanding at the inner radius and contracting at the outer radius when bending occurs.

Total Strain in Unbending

Casting Direction Strain



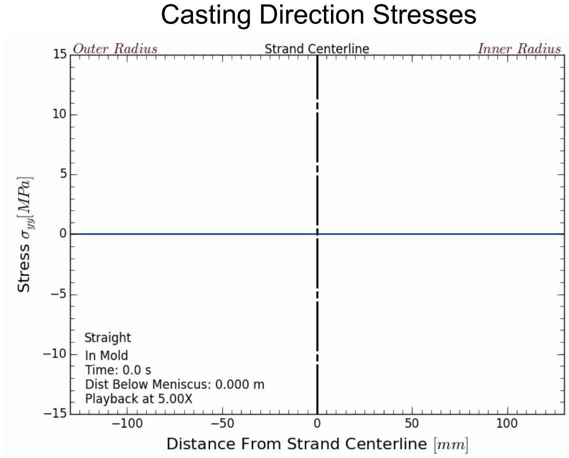
Width Direction Strain



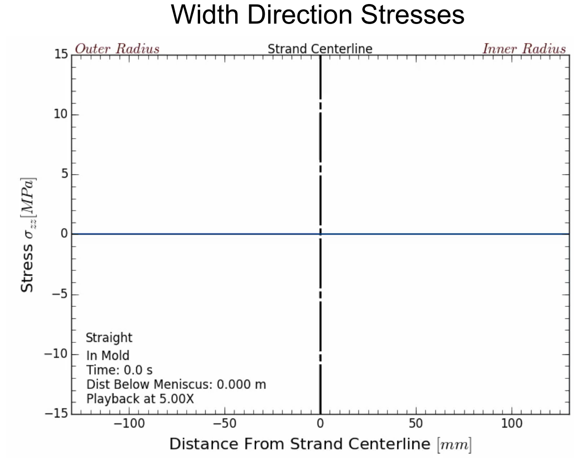
- Total strain in Z-direction does not return to a constant value after unbending. OR maintains larger total strain than IR after unbending.
- For a 1.5m wide casting, this Z-direction strain difference corresponds to a difference of 1.5mm in width at the inner radius and outer radius.

Effects of Thermal Cycling and Bending on Stress Profile

Casting Direction Stresses



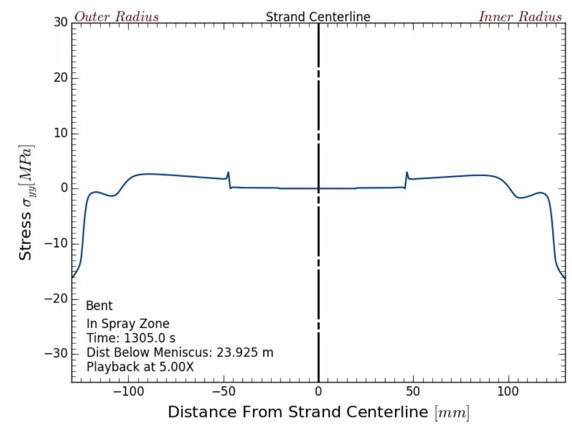
Width Direction Stresses



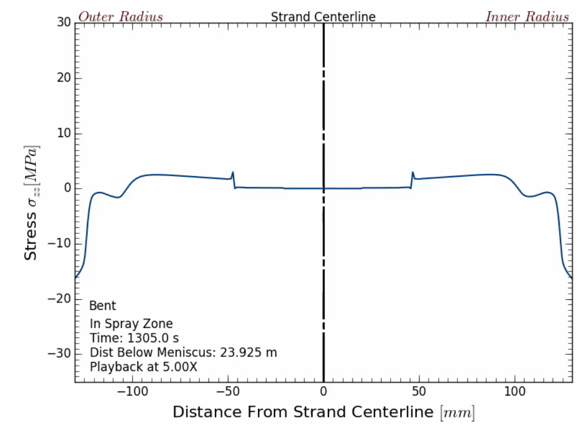
- The σ_{yy} stress profile oscillates due to the thermal cycling in the spray zone before bending begins.
- When bending starts, σ_{yy} is most affected while bending occurs.
- After bending is applied to the model domain, the σ_{yy} stress profile returns to its original shape in approximately 25 seconds.

Effects of Unbending on Stress Profile

Casting Direction Stresses

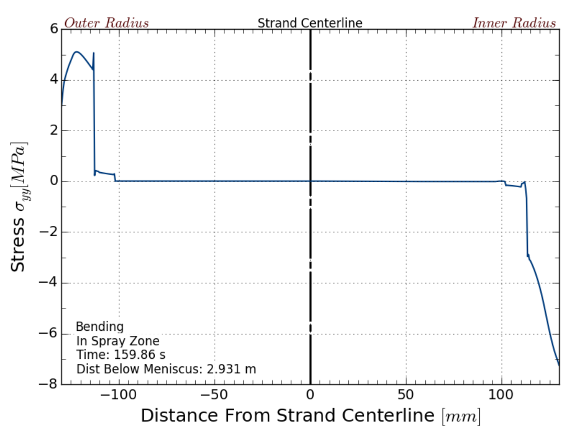


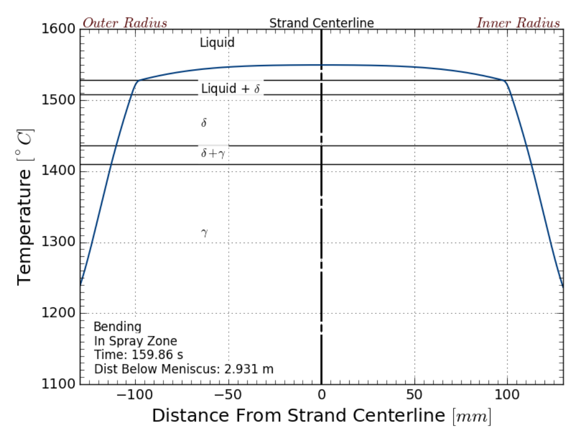
Width Direction Stresses



- After unbending is applied to the model domain, the σ_{yy} stress profile returns to its original shape in approximately 125 seconds.
- Stress cycling is limited to 35mm below the inner and outer radii surfaces.

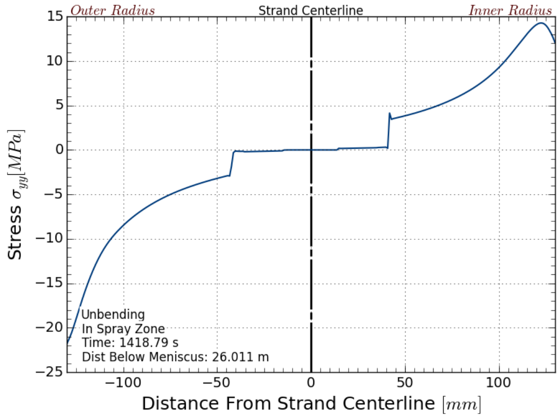
Bending and Shell Temperatures

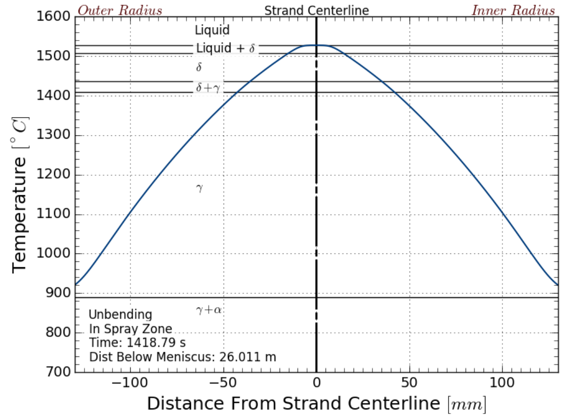




- During bending the solidifying shell reaches peak stresses of 5 MPa and -7 MPa at the outer and inner radii, respectively.
- The shell is 27 mm thick during bending start at 2.83 m below the meniscus.

Unbending and Shell Temperatures

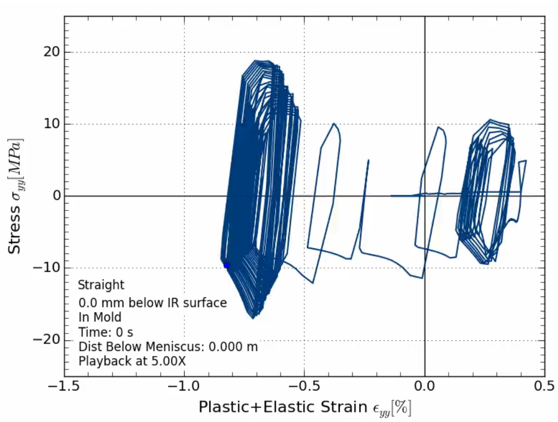




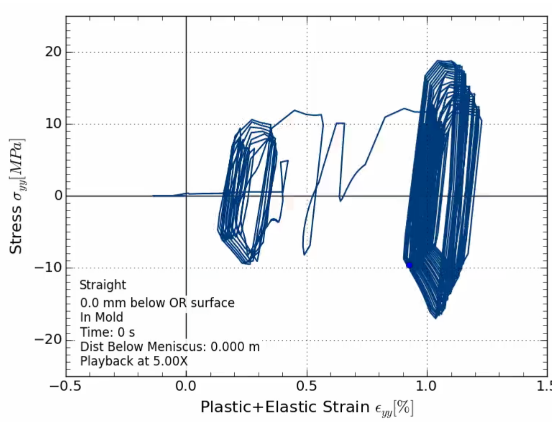
- During unbending the solidifying shell reaches average stresses of -22 MPa and 14 MPa at the outer and inner radii, respectively.
- The shell is 114 mm thick when unbending starts at 25.78 m below the meniscus.

Surface Stress Cycling in Bending

Inner Radius Surface



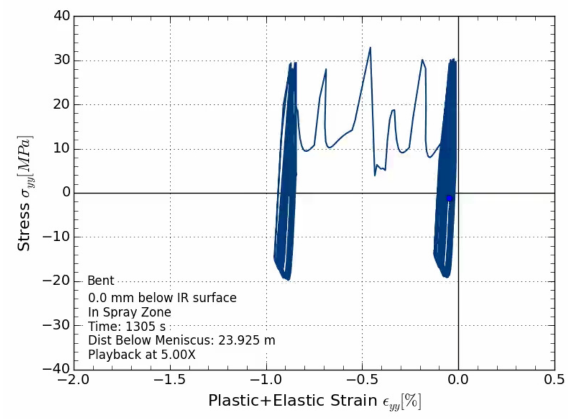
Outer Radius Surface



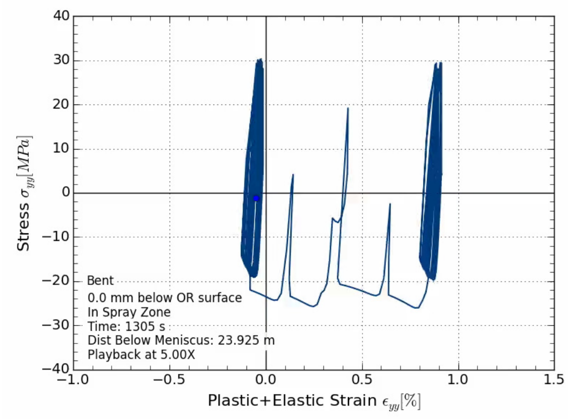
- The maximum tensile stresses at the inner radius shell surface do not increase significantly from bending.
- The outer radius experiences tension, and the inner radius experiences compression.
- The stress cycles become larger with time.

Surface Stress Cycling in Unbending

Inner Radius Surface



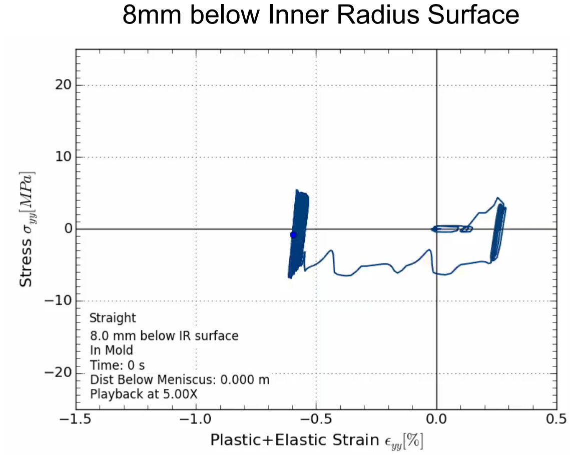
Outer Radius Surface



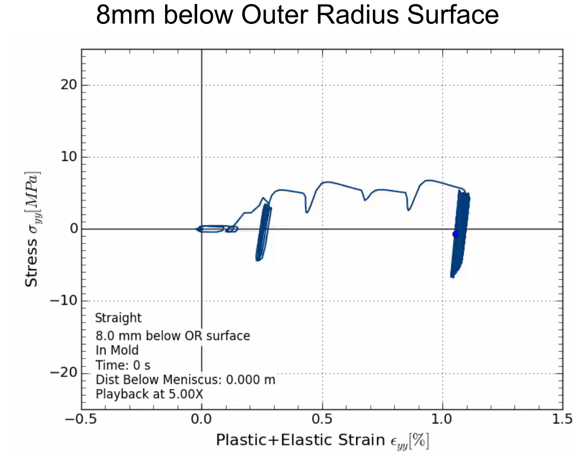
- The maximum tensile stresses at the inner radius shell surface do not increase significantly from unbending.
- However, the inner radius experiences only tensile stresses and increasing tensile inelastic strains for several cycles during unbending.
- While mostly compressive, the outer radius experiences some tensile stresses during unbending.

Subsurface Stress Cycling in Bending

8mm below Inner Radius Surface



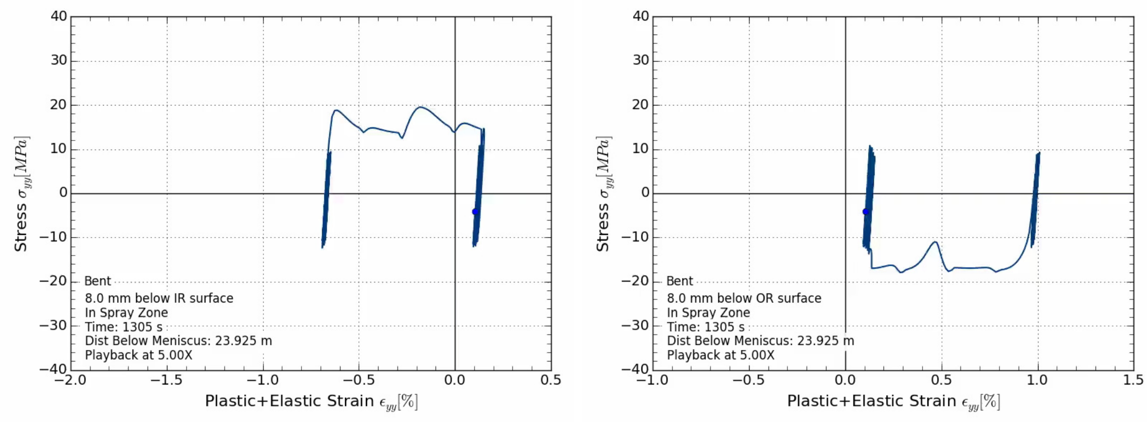
8mm below Outer Radius Surface



- The $\Delta\sigma$ and $\Delta\varepsilon$ of the subsurface stress cycles is less than the surface stress cycles.
- The maximum tensile stresses at 8mm subsurface are experienced in between water spray and roll contact, caused by the surface reheating

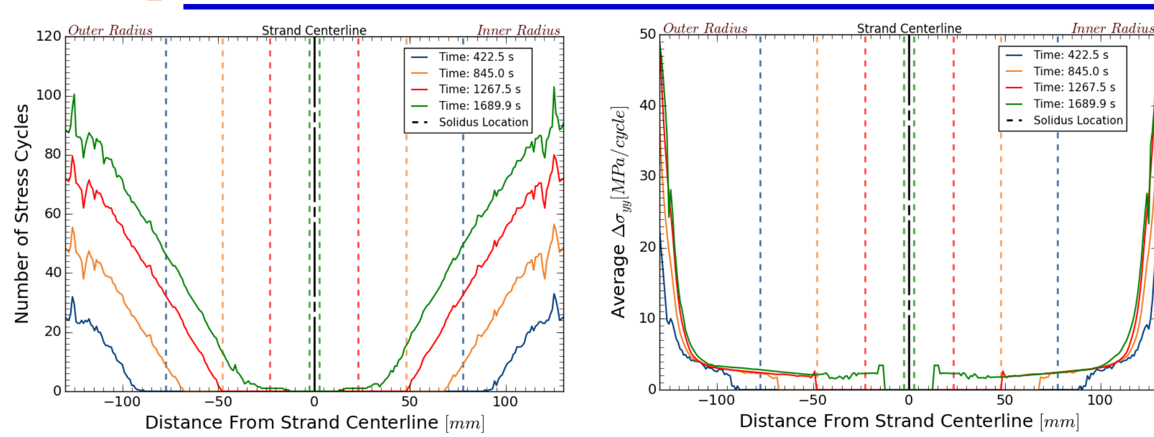
Subsurface Stress Cycling in Unbending

8mm below Inner Radius Surface | 8mm below Outer Radius Surface

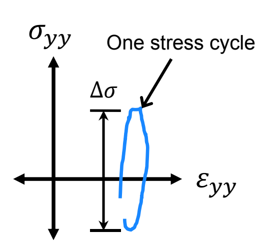


- The $\Delta\sigma$ and $\Delta\varepsilon$ of the subsurface stress cycles is less than the surface stress cycles.
- The maximum tensile stresses at 8mm subsurface are experienced in between water spray and roll contact.

Stress Cycles Through Thickness



- Peak σ_{yy} stress cycle count of 100 at ~5 mm below shell surface.
- Stress cycles counted by recording local minimum and maximum stresses and then using rainflow algorithm from Amzallag[2].
- Cycles only counted if $\Delta\sigma > 0.5MPa$.



Thermal Results

- The Abaqus model surface temperatures agree very well with the CON1D surface temperatures.
- The fluctuation of shell surface temperature is approximately 100°C for each spray nozzle.
- Near the end of the of the caster, the surface temperatures fluctuate about the $\gamma \rightarrow \gamma+\alpha$ transition temperature.
- The thermal model ran in 23.0 minutes.

Mechanical Results

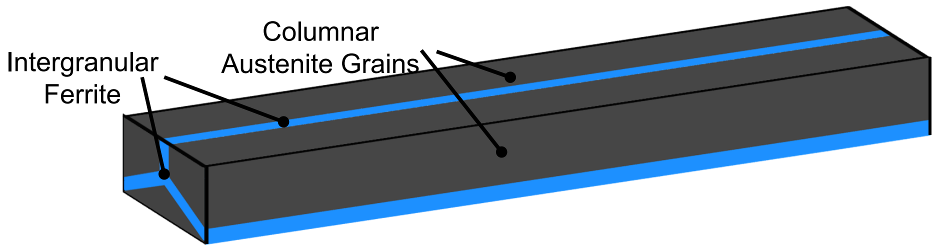
- The shell surface experiences a total of 88 stress reversals due to thermal cycling in the spray cooling zone.
- Unbending creates 3x larger stresses for 5x longer times than bending.
- Bending and unbending creates final (residual) width differences of 0.1% (1-2mm) between the inside and outside radii.
- The average magnitude of stress cycles decreases rapidly with distance below shell surface.
- The mechanical model ran in 1.12 hours.

Conclusions

- The effects of thermal cycling in the spray cooling zone on shell stresses decrease rapidly with distance below shell surface.
- The inner radius surface during unbending is most susceptible to crack formation; it experiences mean tensile stress while inelastic strain increases in tension.
- The mechanical effects of thermal cycling from the spray zone start to crack formation must be accounted for when modeling the formation of transverse cracks.
- A new computational model to predict thermo mechanical behavior of a solidifying steel shell from the meniscus through spray cooling has been developed.

Future Work

- Parametric studies with this fast 1-D modeling tool to investigate effects of casting conditions, bulging, etc.
- Use as a framework for 3-D thermo mechanical modeling including microstructural features to predict ductility:
  - Modify this modeling tool into a micro model that includes microstructural features such as columnar austenite grains with grain boundary ferrite and/or precipitates.
  - Use a macro scale model to determine the bending and bulging conditions experienced by the shell.
  - Link the macromodel bending and bulging results to the micromodel via boundary conditions.



Acknowledgments

- Continuous Casting Consortium Members (ABB, AK Steel, ArcelorMittal, Baosteel, JFE Steel Corp., Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp., Nucor Steel, Postech/ Posco, SSAB, ANSYS/ Fluent)
- Professor Brian Thomas, Dr. Lance C. Hibbeler

References

1. *ABAQUS 6.13 User's Manual*. (2013). SIMULIA.
2. Amzallag, C., et al. "Standardization of the rainflow counting method for fatigue analysis." *International journal of fatigue* 16.4 (1994): 287-293.
3. *CON1D 10.10.01 Users Manual*, (2010).