CCC Annual Report

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Heat Transfer, Bulging and Machine Taper Modeling

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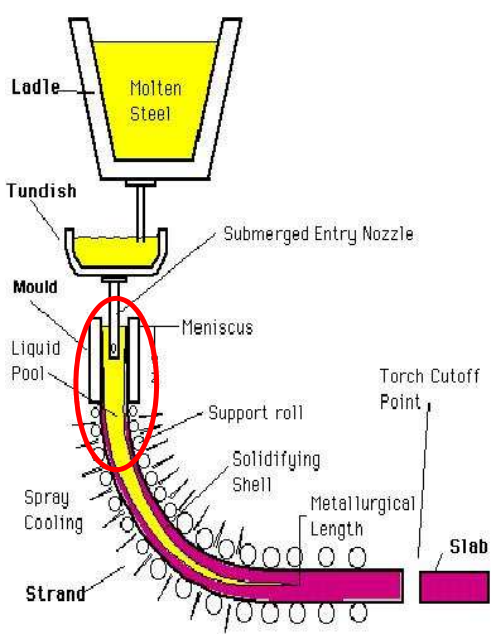
Objective



- Longitudinal cracks are generally caused by unstable fluctuation of top liquid surface at meniscus
- Caster domain of interest: first segment below mold exit
  - ➢ Vertical segment with only support rolls
  - ➢ Largest liquid volume region
  - ➢ Thin shell prone to bending (bulging)
  - ➢ Machine taper design

Modeling Steps

1. Heat transfer modeling

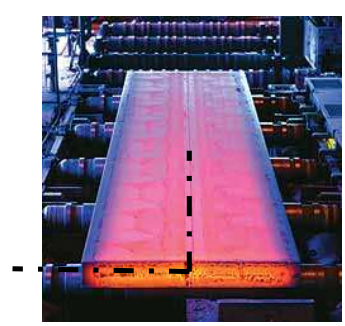
- Full ¼ rectangular domain is chosen
- Heat flux boundary of wide face and narrow face are input by user subroutine (Dsflux) in Abaqus

2. Stress modeling

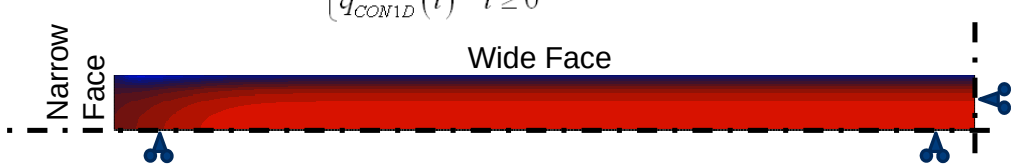
- L-shape domain is chosen for simulating shell bending. The center part of rectangular domain in heat transfer modeling, which are always kept to be liquid, is removed in simulation
- Temperature of corresponding nodes are read from heat transfer modeling
- The bulging profiles are applied as rigid wall boundary

Heat Transfer Boundary Conditions for Transverse Slice

- CON1D calibrated surface heat flux profile for wide face includes convection from sprays, conduction through roll contact, and radiation
- Heat flux for narrow face only includes radiation after mold exit
- Ferrostatic Pressure (ρgH) applied uniformly over wide and narrow faces



$$q_{WF}(t) = \begin{cases} 0 & t < 0 \\ q_{CON1D}(t) & t \geq 0 \end{cases}$$

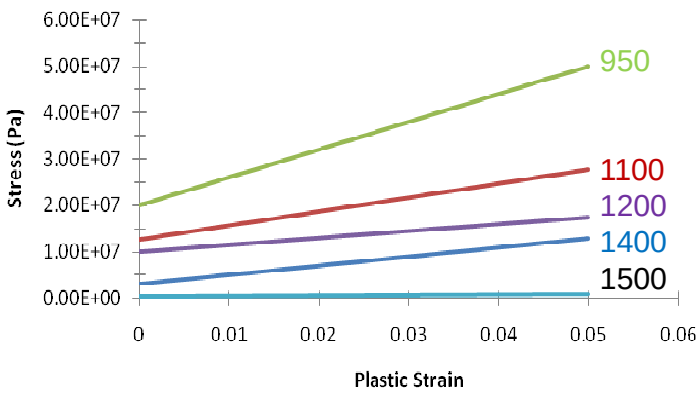


$$q_{NF}(t) = \begin{cases} 0 & t < 0 \\ 0.85 q_{WF}(t) & t_{moldexit} > t \geq 0 \\ \varepsilon_{steel}\sigma(T_s^4 - T_{air}^4) & t > t_{moldexit} \end{cases}$$

Casing speed=17.333 mm/s, pour temperature=1538°C

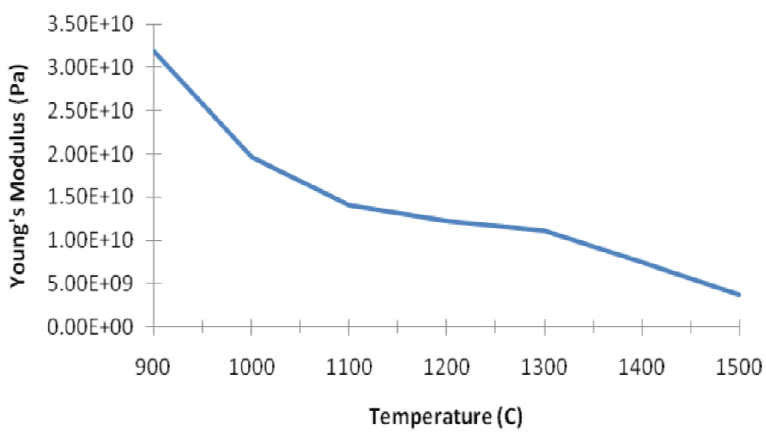
Thermal-Elastic-Plastic Stress-Strain Data

Yield Stress versus Plastic Strain in 1-D tensile test
For Elastic-Thermal-Plastic Analysis in Abaqus



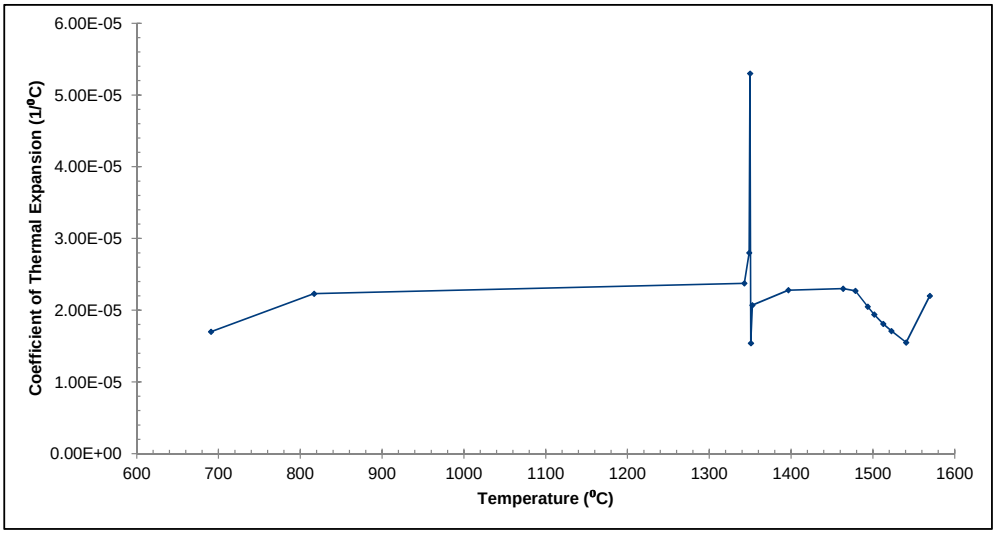
Stress (Pa)	Plastic Strain	Temperature (C)
2.00E+07	0	950
5.00E+07	0.05	950
1.27E+07	0	1100
2.77E+07	0.05	1100
1.00E+07	0	1200
1.75E+07	0.05	1200
3.00E+06	0	1400
1.30E+07	0.05	1400
5.00E+05	0	1500
1.00E+06	0.05	1500

Elastic Modulus



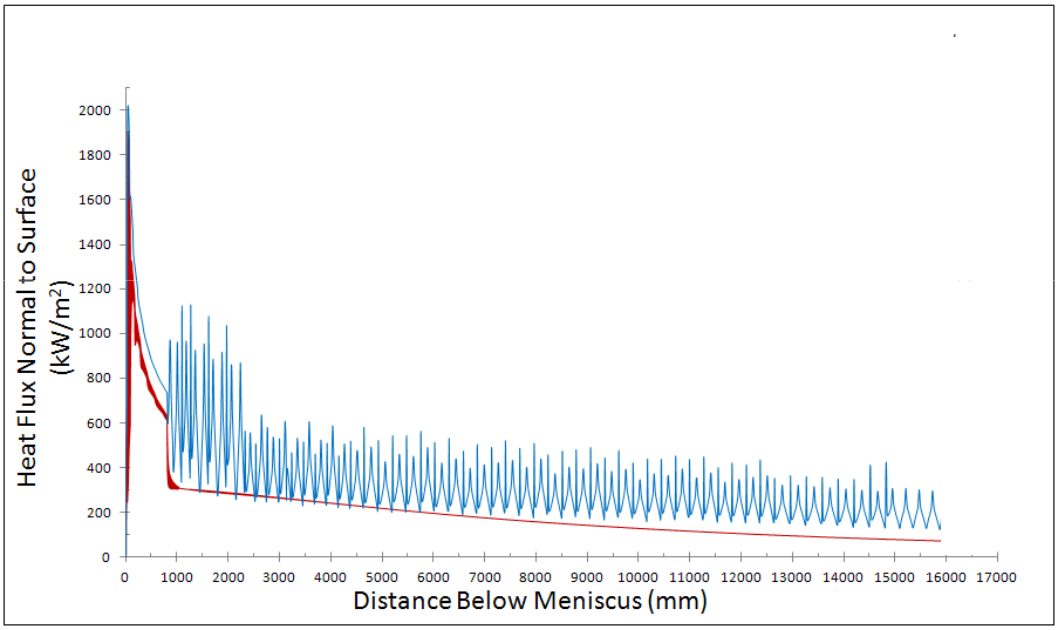
Young's Modulus (Pa)	Temperature (C)
3.20E+10	900
1.96E+10	1000
1.40E+10	1100
1.22E+10	1200
1.11E+10	1300
7.51E+09	1400
3.75E+09	1500

Thermal Expansion Coefficient



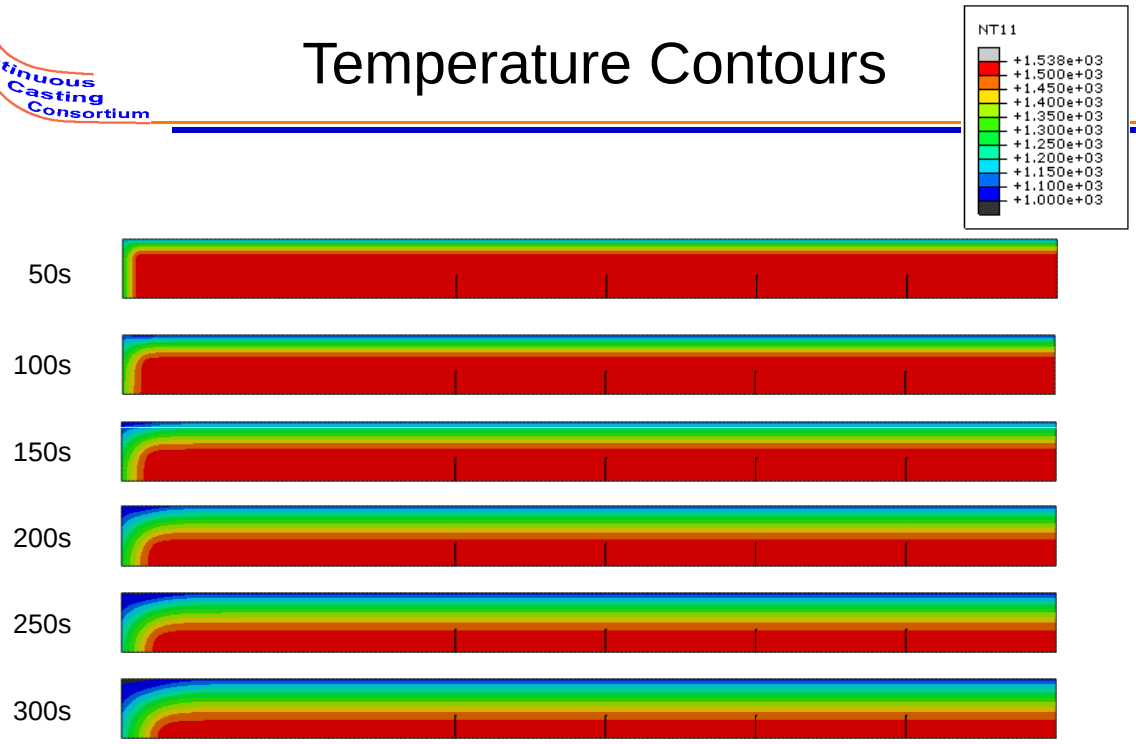
- Ref Temperature 1350°C

Applied Heat Flux

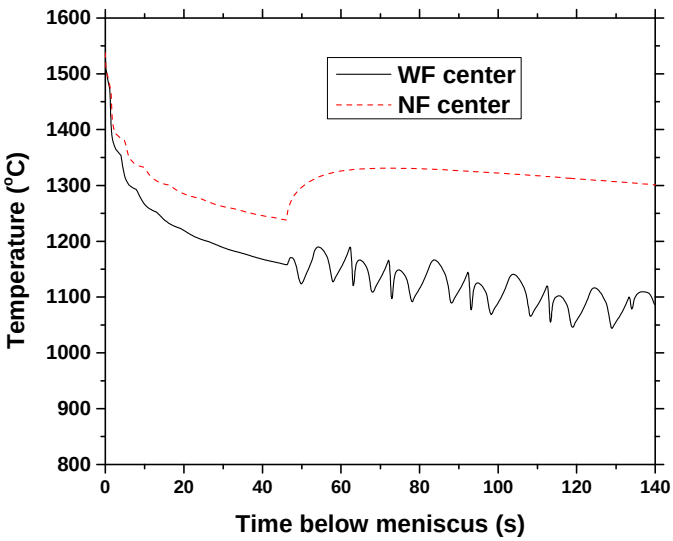


Specifying surface heat flux as function of time are input to Abaqus

Temperature Contours

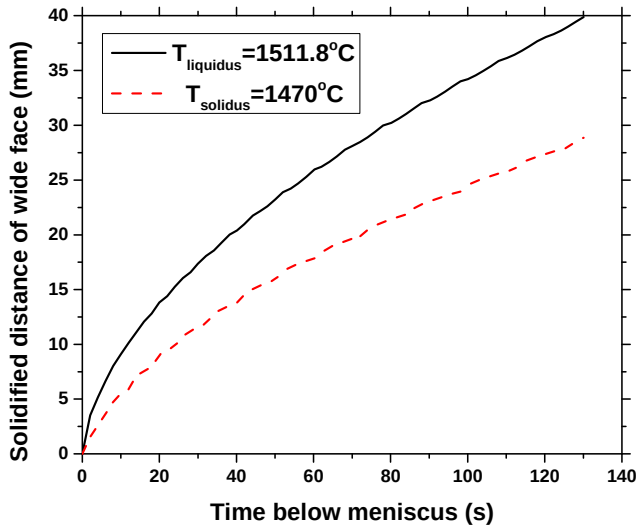


Surface Temperature



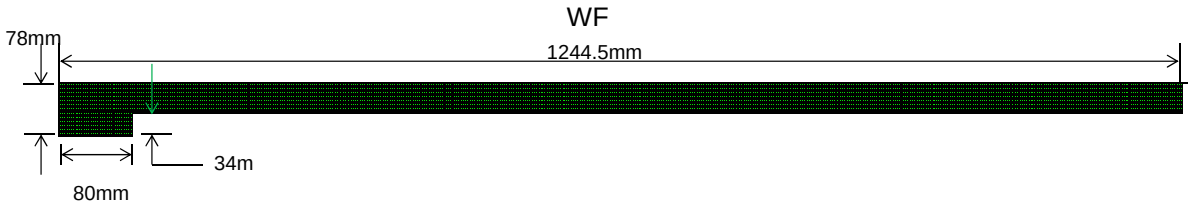
- WF shows temperature oscillations due to water spray cooling

Shell Development



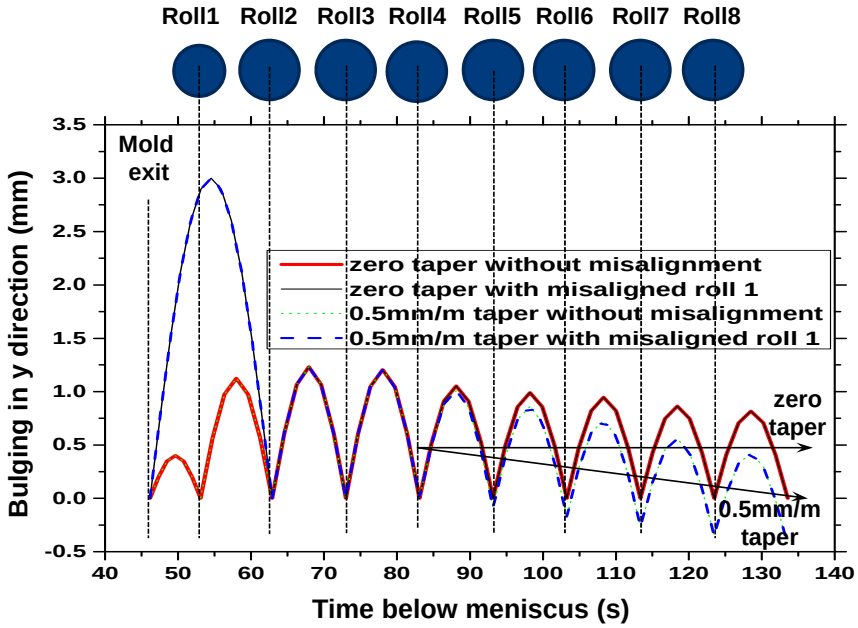
➢ Compared with slab thickness of 78mm, the shell is only partly solidified for the simulation time of 130s

L-shape Domain Mesh of Stress Model



- Read temperature profiles for the corresponding nodes from the full rectangular mesh of thermal simulation
- Elements which remain purely liquid up to 130s are removed for mechanical simulation
- Rigid wall is applied to be mold wall or bulging boundary (steel shell can approach, but not penetrate rigid wall)
- 2x2mm general plain strain elements

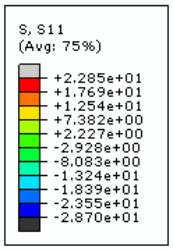
Prescribed Displacement in Allowed Bulging Profiles



- First roll is 120 mm (~6.2s) from mold exit
- Segment zero roll every 175 mm (~10.1s) after first roll
- Bulging is estimated by empirical equation and sine shape assumption

Deformation and Stress Contour Histories

- For the case of 0 taper and no misalignment
- Deformation factor=10



Mold exit (46.2s)

Between mold exit and Roll 1 (49.6s)

Roll 1 (53.1s)

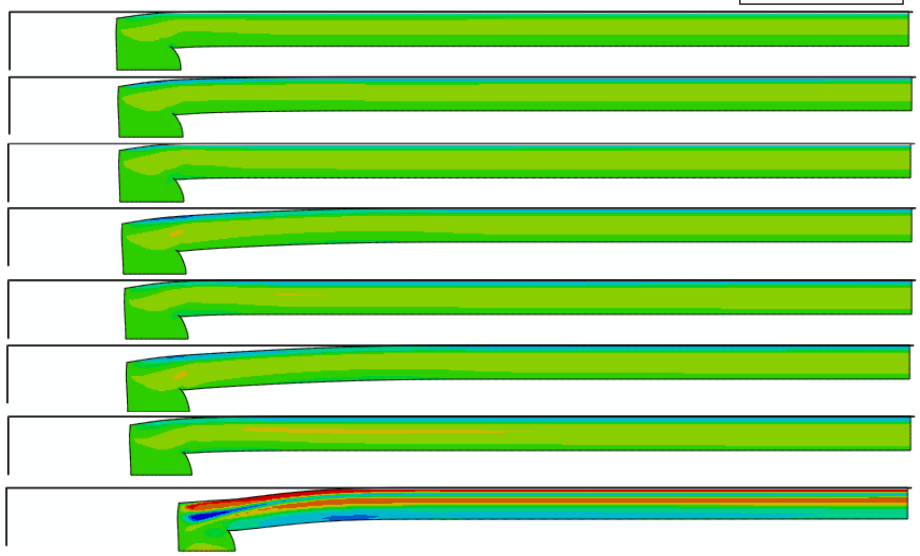
Between roll 1 and 2 (58.0s)

Roll 2 (62.9s)

Between roll 2 and 3 (67.9s)

Roll 3 (73.0s)

130s (end of simulation)

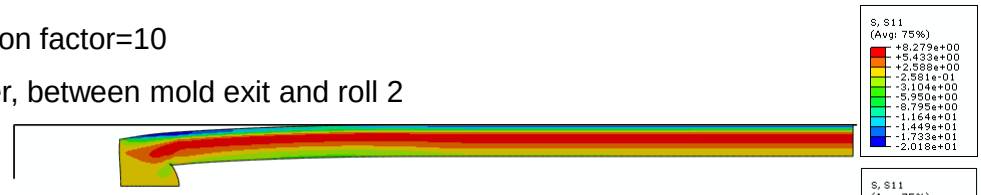


Influence of Misalignment and Machine Taper on Bending

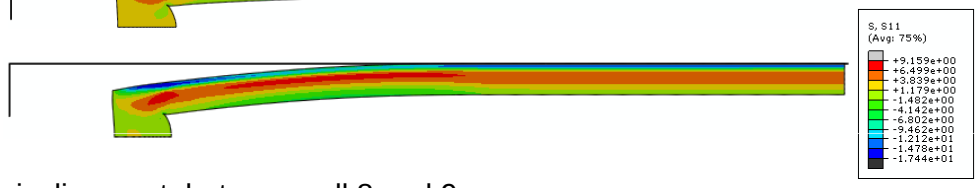
❖Deformation factor=10

➢ Zero taper, between mold exit and roll 2

No misalignment (58.0s)

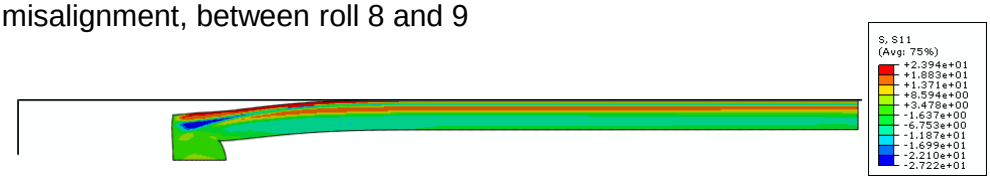


Misaligned roll 1 (54.5s)

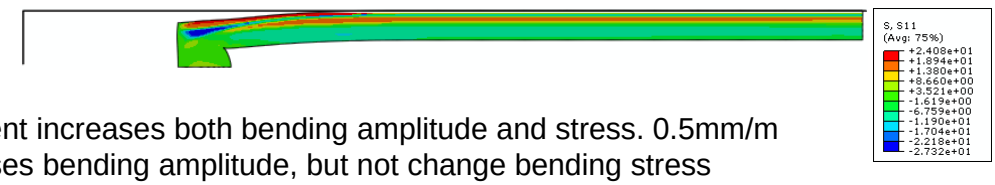


➢ Without misalignment, between roll 8 and 9

Zero taper (128.5s)



0.5mm/m taper (128.5s)



✓ Misalignment increases both bending amplitude and stress. 0.5mm/m taper decreases bending amplitude, but not change bending stress

Liquid Area and Volume Calculation

- To calculate the liquid area for any time, the following equation for polygon (convex or concave) is used

$$A = \frac{1}{2}\left|\sum_{i=1}^{n}(x_i y_{i+1} - x_{i+1} y_i)\right| \quad \& \ Let\ x_{n+1} = x_1, y_{n+1} = y_1$$

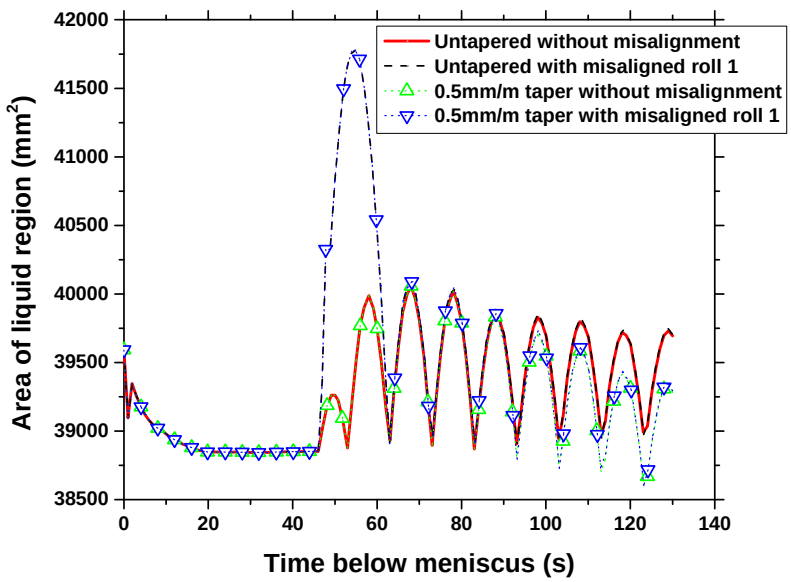
❖ The nodes must be ordered clockwise or counterclockwise, and the starting point must be included twice

- The liquid volume is obtained by integrating the liquid area with time

$$V_{(t_1,t_2)} = V_c \int_{t_1}^{t_2} A(t)dt \approx V_c(t_2 - t_1)\frac{A(t_1) + A(t_2)}{2}$$

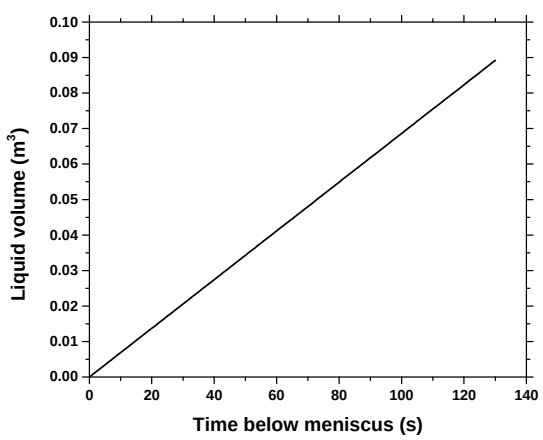
❖Calculated region is only omitted area in the center of L-shape domain. The displacements of all nodes on boundary of this area are recorded for each time step

Area of Liquid Region

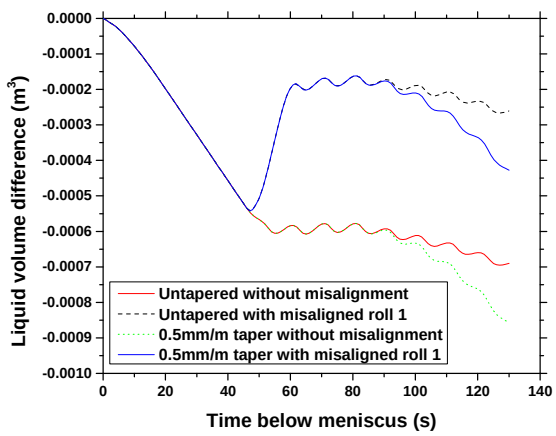


- Misaligned roll 1 greatly increases bulging amplitude and liquid area between mold exit and roll 2, but has minor influence after slab passes roll 2
- 0.5mm/m taper decreases the bulging amplitude and liquid area comparing with zero taper. It also makes the shape of liquid area between 2 neighboring rolls very asymmetric

Calculated Liquid Volume



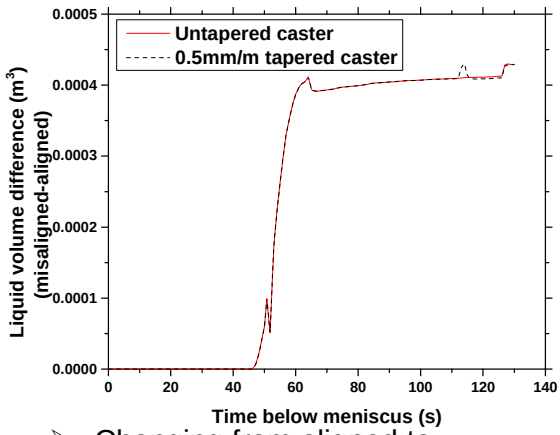
Base value: no shrinkage, no misalignment, no taper



Subtracting base value for all cases

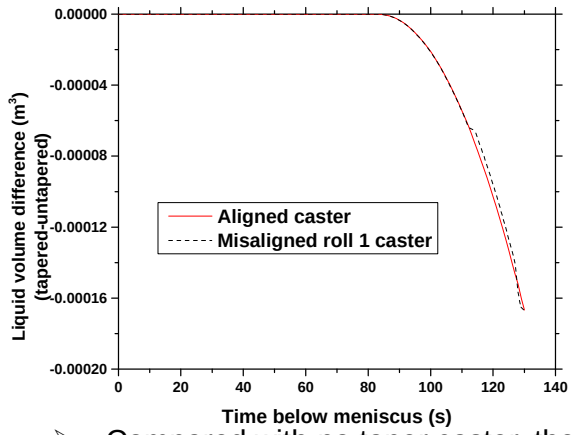
Influence of Misalignment and Machine Taper on Liquid Volume Change

Difference between misaligned and aligned casters



- Changing from aligned to misaligned, liquid volume increases by ~429000mm^3
- This corresponds to a drop of 10.8mm of top fluid surface

Difference between tapered and untapered casters



- Compared with no taper caster, the tapered caster liquid volume decreases by ~167000mm^3
- Without considering dynamics, this has no influence on top fluid surface

Conclusions

1. Coupled heat transfer and stress models show that steel shell bends up when bulging occurs.

2. Larger bulging amplitude always increases the containing liquid volume .

3. A sudden misalignment of a single roll greatly increases the bulging amplitude and the liquid volume, which will likely cause a drop of the top liquid surface.

4. A machine taper of 0.5mm/m decreases the bulging amplitude and the liquid volume. The taper needs to be better designed to make the top fluid surface to keep at the same level.

Future Work

1. Use better thermal-elastic-plastic properties in simulation.

2. Simulation of 2D longitudinal slice to get better and more accurate bulging profiles.

3. Make transient change of practical casting conditions (casting speed, misalignment of rolls, varied mold and machine taper, …) to calculate the real change of the actual top liquid surface.

Acknowledgments

- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Magnesita Refractories, Nippon Steel, Nucor Steel, Postech/ Posco, Severstal, SSAB, Tata Steel, ANSYS/ Fluent)
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