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Thermal Stress Cracking of Sliding Gate Plates

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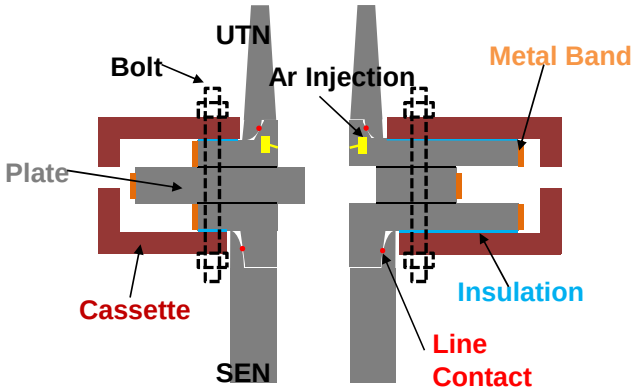
Objectives

- Evaluate possible mechanisms for crack formation

- Explore thermal and mechanical stress in a sliding gate plate during preheating and casting induced by thermal expansion and/or mechanical movement

- Predict crack formation

Research Background



Schematic of Sliding Nozzle System

- **Why are cracks in sliding gate a concern?**
  - **Safety problem (Steel leakage)**
  - **Clogging (Air penetration)**
  - **Productivity Issue**

Type of Cracks

Bottom view of used plate

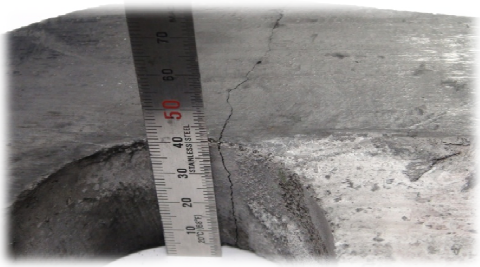
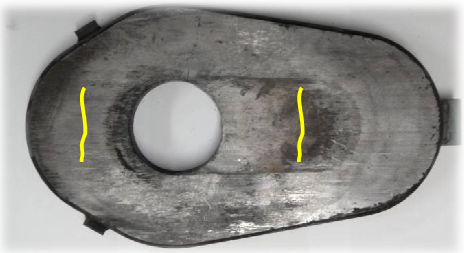


Photo of common through-thickness crack



Schematic of rare cracks locations

Cross section view of common crack

* Refractory component: 85% Alumina, 7% Zirconia, 8% Graphite

Understanding of cracking

- **Through-thickness cracks commonly form during the C.C. process**

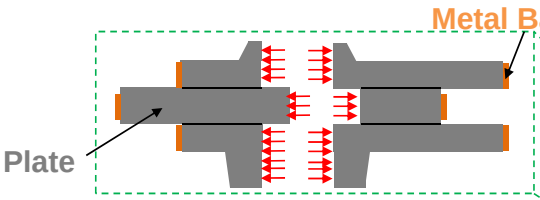
→If these cracks are serious, air penetration can occur: White area on the crack surface indicates that graphite in sliding plate is oxidized
→This suggests that steel is being oxidized

- **Sometimes, different type of cracks can form, likely caused by abnormal non-uniform cassette pressure on middle of plate (not always through-thickness)**

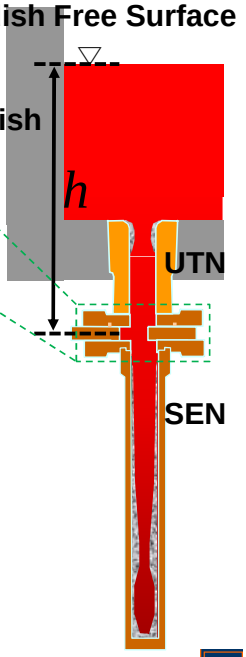
Possible Mechanisms of Common Crack Formation

- **Thermal stress induced by temperature distribution of sliding plate with pre-heating and molten steel temperature**
- **High surface pressure from cassette bolted to the 3 sliding gate plates**
- **Friction force caused by mechanical movements for stabilizing the mold meniscus level**
- **Ferro-static pressure due to height difference between tundish free surface and sliding gate location**

Parameters Considered for Modeling



Schematic of sliding plate front view



Ferrostatic Pressure	$\gamma h = \rho g h$ $= 7020\ \text{kg/m}^3 \times 9.81\ \text{m/s}^2 \times 1.8\ \text{m}$ $\approx 0.124\ \text{MPa}$
Thermal Expansion	$\frac{F}{A} = -E \cdot \alpha \cdot \Delta T$ $= -65 \times 10^9\ \text{Pa} \times 8.367 \times 10^{-6}\ ^\circ\text{C}^{-1} \times 1000\ ^\circ\text{C}$ $\approx -540\ \text{MPa}$

Comparing with thermal expansion pressure, ferrostatic pressure is negligible

Internal Gas Temperature Prediction

- **Pre-heating**

Sliding gate is heated from room temperature to pre-determined temperature

LNG (Liquefied Natural Gas) composition [1]

- Methane(CH4): 88%
- Ethane(C2H6): 5%
- Propane(C3H8):5%
- Butane(C4H6): 2%

→ **Singh VBA model [2] is used**
Flame Temperature: 1518.3 ° C

Internal gas temp. is lower than flame temp.
→ 750 ° C is assumed

Heat Transfer Coefficient of Preheating

Free convection : Churchill and Chu equation[3] is used

$$\overline{Nu} = \left\{ 0.825 + \frac{0.387 Ra^{1/6}}{[1+(0.492/\mathrm{Pr})^{9/16}]^{8/27}} \right\}^2 \qquad h = \frac{Nu \cdot k}{2r}$$

→ $h_{o,preheat}$ = 7 W/m²·K

Forced convection : Petukhov, Kirillov and Popov equation[3] is used

$$Nu = \frac{[(f/8)\,\mathrm{Re}_D\,\mathrm{Pr}]}{[1.07+12.7(f/8)^{1/2}(\mathrm{Pr}^{2/3}-1)]} \qquad h = \frac{Nu \cdot k}{2r}$$

→ $h_{i,preheat}$ = 65 W/m²·K

Forced Heat Transfer Coefficient of Molten Steel

- **Molten steel**

Molten steel flows through sliding plate bore (1550ºC)

Sleicher and Rouse Equation[3] is used to calculate forced heat transfer coefficient

$$\mathrm{Re} = \frac{2ur}{\upsilon} \qquad \mathrm{Pr} = \frac{\upsilon}{\alpha} \qquad a = 0.88 - \frac{0.24}{4+\mathrm{Pr}} \qquad b = \frac{1}{3} + 0.5Exp(-0.6\,\mathrm{Pr})$$

$$Nu = 5 + 0.015\,\mathrm{Re}^a\,\mathrm{Pr}^b \qquad h = \frac{Nu \cdot k}{2r}$$

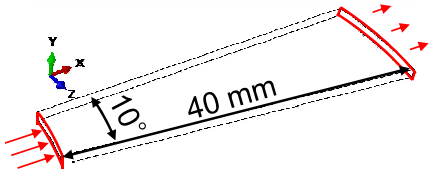
→**The forced heat transfer coefficient from molten steel flow was calculated to be 28.7 x 10³ W/m²·K**

Test Problem of Transient Heat Conduction
Abaqus Model Validation with Singh VBA Model

Schematic of test problem

t = 120 min.
$T_{initial}$ = 20 °C

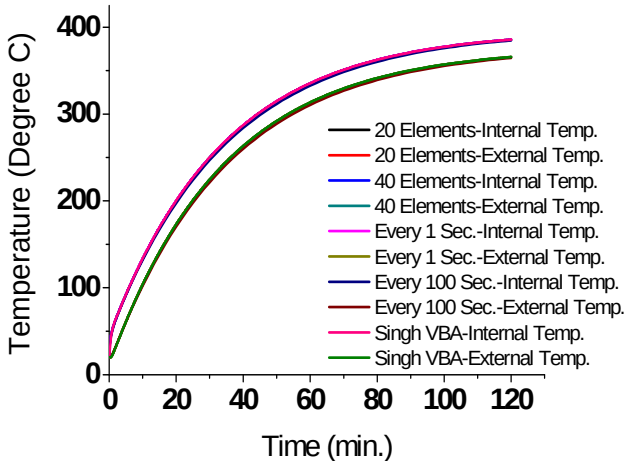
h_o = 20 W/m²K
T_o = 20 °C



h_i = 70 W/m²K
T_i = 600 °C

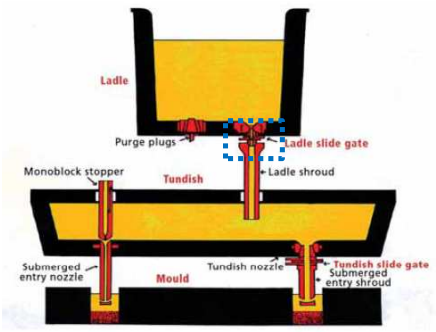
k = 20 W/mK
ρ = 2460 kg/m³
C_p = 1500 J/kgK

*Other surfaces are insulated

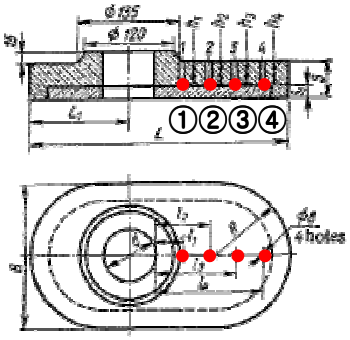


- 20 and 40 elements results match
- Time step of every 1 sec. and 100 sec. models match
→The 100 sec. time step is used to tundish sliding gate model
- Abaqus model matchs Singh VBA model

Model Validation Problem – Ladle Plate Heating



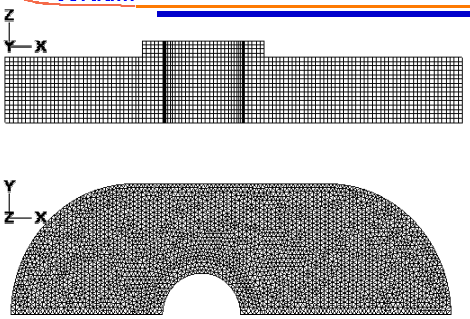
Schematic of casting equipment [4]



Location of thermocouples in plate[5]

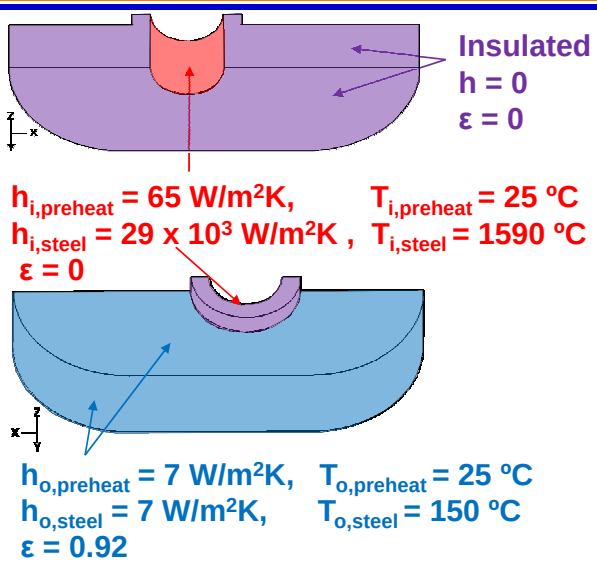
- Ladle plate temperature was measured during top teeming of molten steel into mold
- 4 Thermocouples were installed on upper plate
- Plates were subjected to heat treatment at 170 °C [5]

Heat Transfer Model Validation: Ladle-Plate Heating Problem



Part	Elements
Ladle Plate	(Wedge) 92,378

Finite element mesh



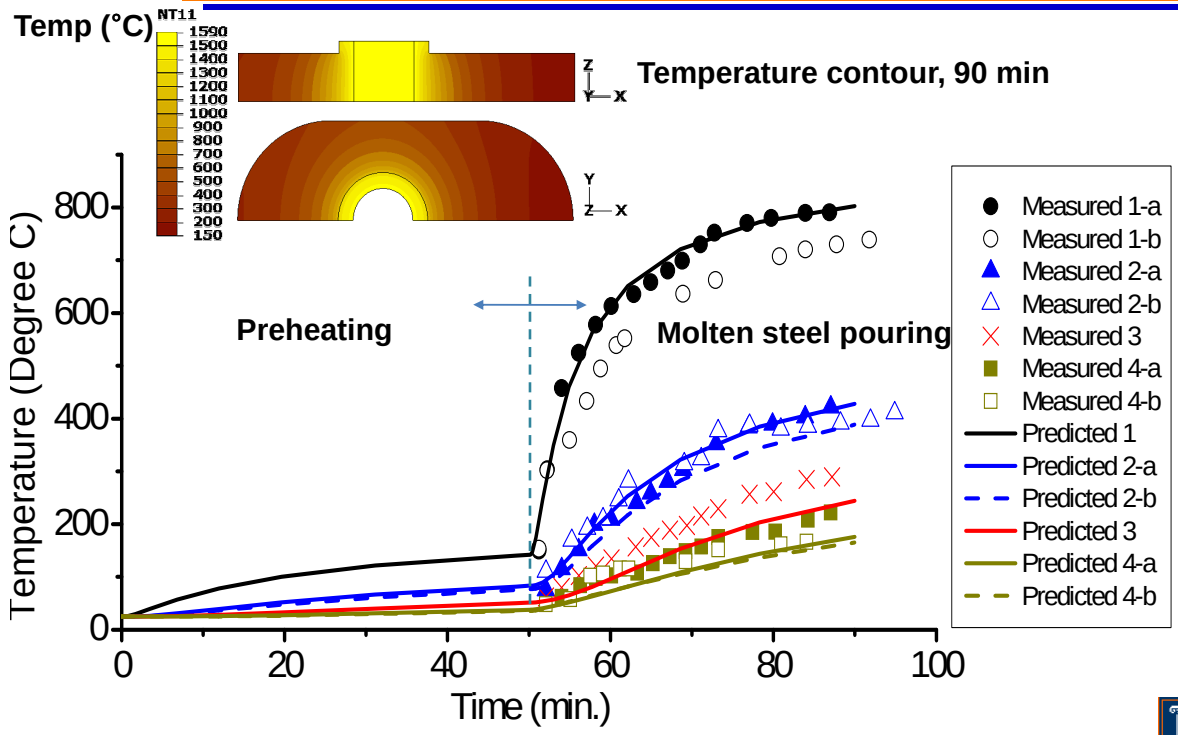
Boundary conditions

Run transient 3-D heat conduction simulation of upper ladle plate, to compare with measurements

Properties for Ladle Plate Model Validation Problem

		Symbol	Value	Units
	Initial Nozzle Temperature	$T_{initial}$	25	°C
Preheating	Internal Gas Temperature	$T_{i,preheat}$	750	°C
	Internal Convection Heat Transfer Coefficient (Forced)	$h_{i,preheat}$	65.24	W/m²·K
	External Ambient Temperature	$T_{o,preheat}$	25	°C
	External Convection Heat Transfer Coefficient (Free)	$h_{o,preheat}$	7	W/m²·K
Casting	Molten Steel Temperature	$T_{i,steel}$	1590	°C
	Internal Convection Heat Transfer Coefficient (Forced)	$h_{i,steel}$	28719.63	W/m²·K
	External Ambient Temperature	$T_{o,steel}$	150	°C
	External Convection Heat Transfer Coefficient (Free)	$h_{o,steel}$	7	W/m²·K
	Density [6]	ρ	3200	kg/m³
	Thermal Conductivity [6]	k	8.26	W/m·K
	Specific Heat [6]	C_p	1004.64	J/kg·°C
	Stefan-Boltzmann Const.	σ	5.669 x 10^{-8}	W/m²·K⁴
	Emissivity [7]	ε	0.92	-

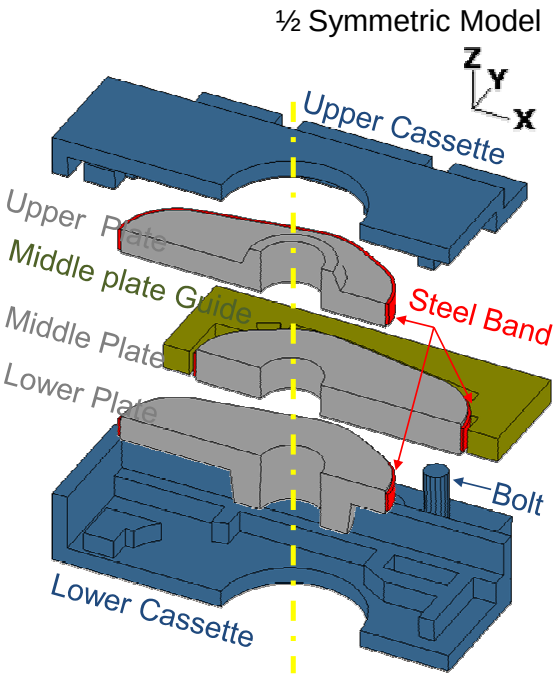
Comparison of Measured and Predicted Temperature in Ladle Plate

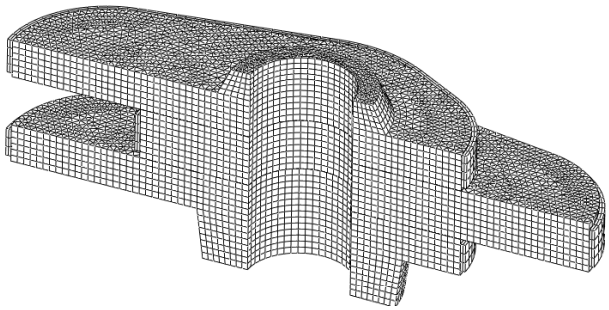


Model Validation Summary

- **Preheating is calculated until #1 T/C is reached to 150°C for 50 min.**
- **During 40 min. casting, experimental and predicted results are well-matched in heat transfer model of ladle plate**
- **Assumed internal gas temperature (750°C) is reasonable to be applied to tundish sliding gate nozzle model for preheating stage**
- **The heat transfer coefficients are used to tundish sliding gate nozzle model**

Tundish Sliding Gate Nozzle Component & Finite Element Mesh





Part	Elements	
Upper Plate	(Wedge)	15,133
Middle Plate	(Wedge)	18,008
Lower Plate	(Wedge)	18,782
Upper Band	(Hex)	512
Middle Band	(Hex)	512
Lower Band	(Hex)	384
Total		52,871

Modeling Approach

Initial Condition
Room Temp.

→ **Pre-heating (750°C)**
Opening Ratio 100%
12600 sec

→ **Mechanical Movement**
100% → 0%
Vel. : 25 mm/sec

↓

Molten Steel Pouring (1550°C)
0%
750 sec

← **Mechanical Movement**
0% → 60%
Vel. : 25 mm/sec

← **Molten Steel Pouring (1550°C)**
60%
12600 sec

Casting Started

↓ **Casting Finished**

Mechanical Movement
60% → 0%
Vel. : 25 mm/sec

→ **Preheating :3 hr 30 min**
C.C : 3 hr 30 min

Properties for Tundish Sliding Gate Heat Transfer Model

			Symbol	Value	Units
	Initial Nozzle Temperature		$T_{initial}$	25	°C
Preheating	Internal Gas Temperature (Preheating)		$T_{i,preheat}$	750	°C
	Internal Convection Heat Transfer Coefficient (Forced)		$h_{i,preheat}$	65.24	W/m²·K
	External Ambient Temperature (Preheating)		$T_{o,preheat}$	25	°C
	External Convection Heat Transfer Coefficient (Free)		$h_{o,preheat}$	7	W/m²·K
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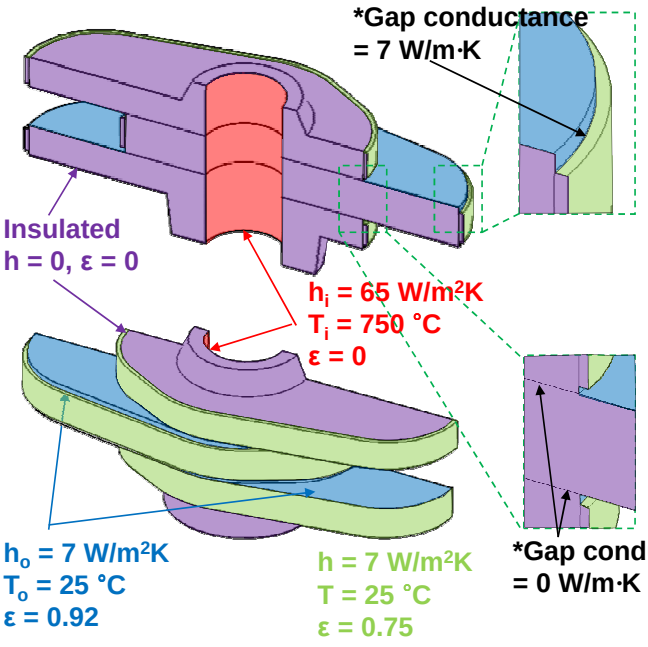
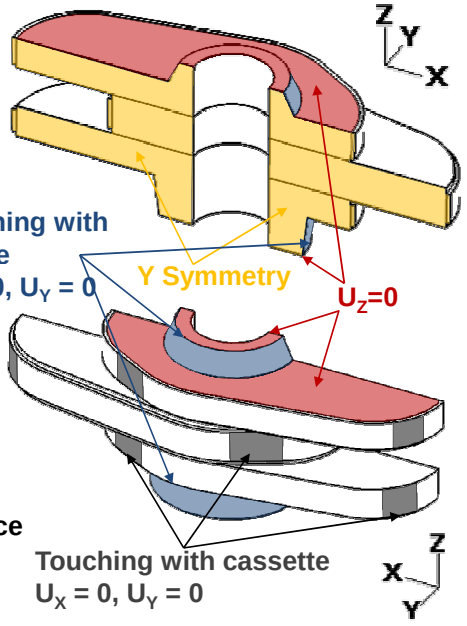
	External Ambient Temperature		$T_{o,steel}$	150	°C
	External Convection Heat Transfer Coefficient (Free)		$h_{o,steel}$	7	W/m²·K
	Refractory [6]	Density	ρ_{ref}	3200	kg/m³
		Thermal Conductivity	k_{ref}	8.26	W/m·K
		Specific Heat	$C_{p,ref}$	1004.64	J/kg·°C
	Steel [6]	Density	ρ_{steel}	7860	kg/m³
		Thermal Conductivity	k_{steel}	48.6	W/m·K
		Specific Heat	$C_{p,steel}$	418.6	J/kg·°C
	Stefan-Boltzmann Const.		σ	5.669×10^{-8}	W/m²·K⁴
	Emissivity [7]		ε_{ref}	0.92	-
			ε_{steel}	0.75	-

Boundary Conditions of Preheating Step

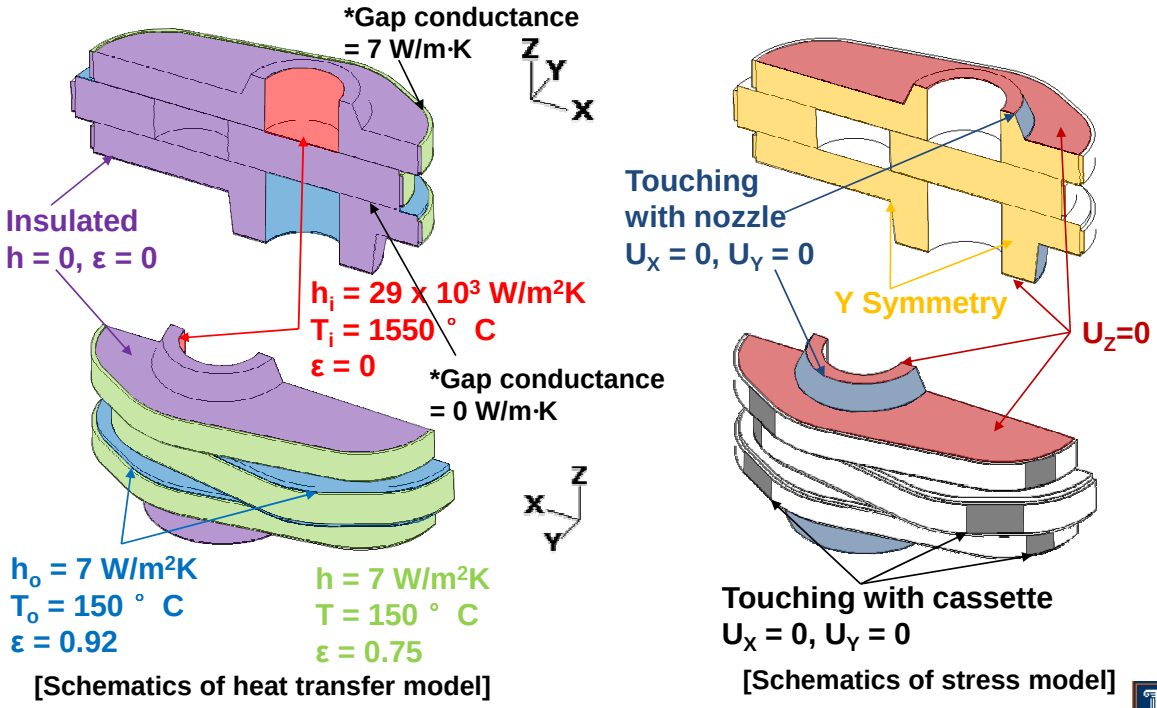


[Schematics of heat transfer model]



[Schematics of stress model]

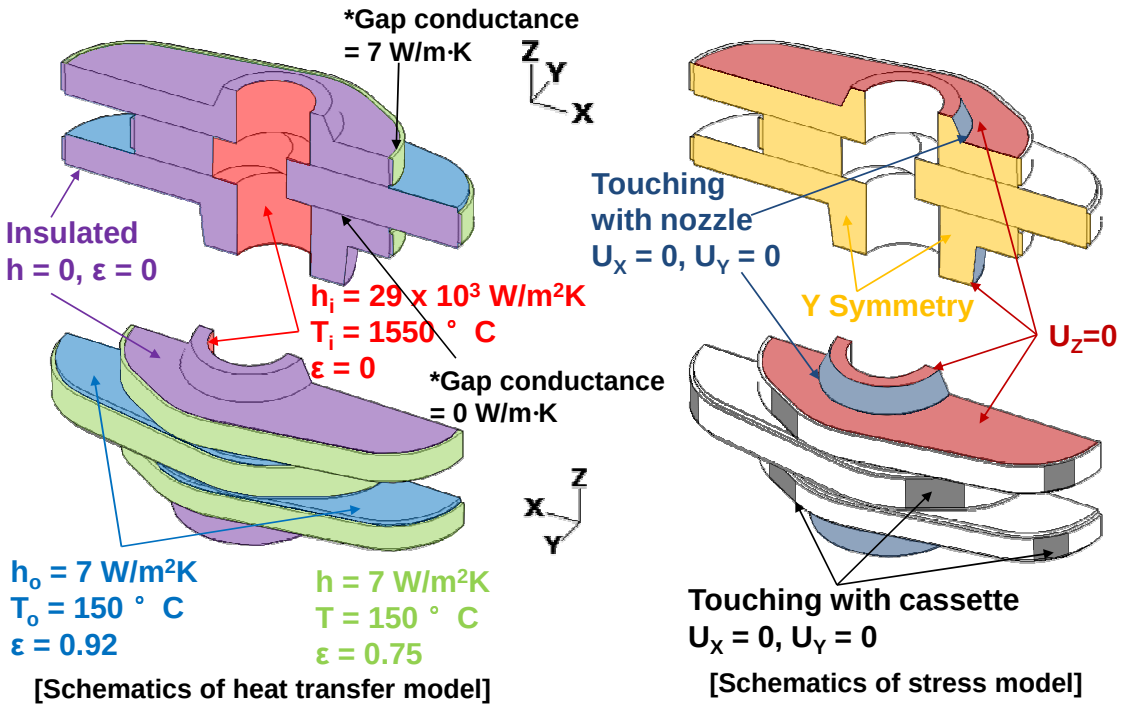
Boundary Conditions of Molten Steel Pouring Step



[Schematics of heat transfer model]

[Schematics of stress model]

Boundary Conditions of Continuous Casting Step

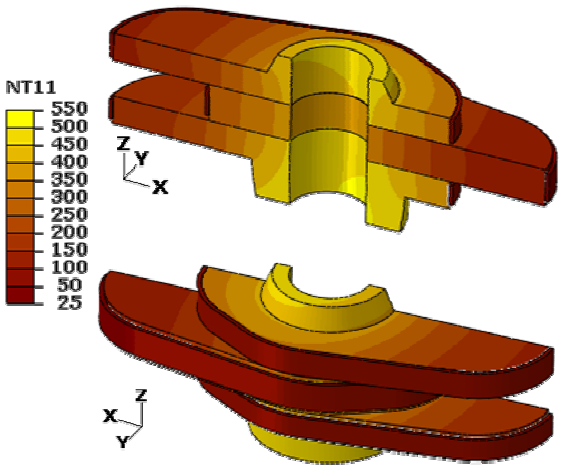


[Schematics of heat transfer model]

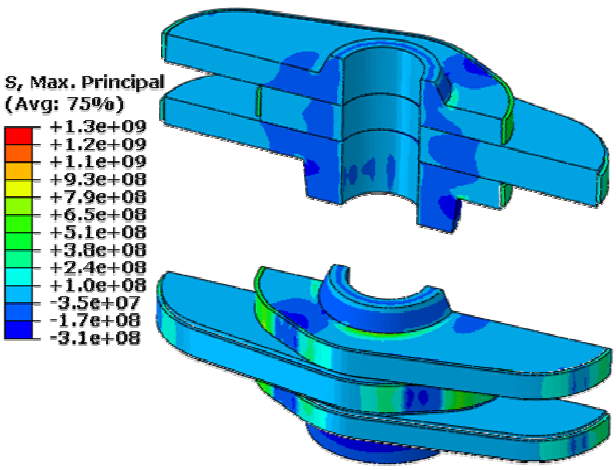
[Schematics of stress model]

Thermo & Mechanical Behavior of Preheating Step

Temperature (°C)

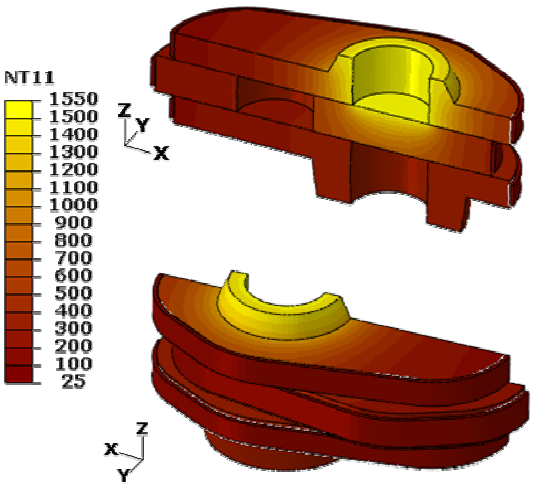


Stress (Pa)

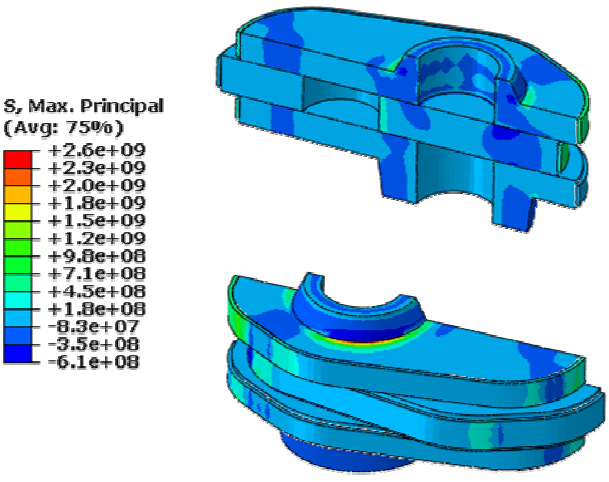


Thermo & Mechanical Behavior of Molten Steel Pouring Step

Temperature (°C)

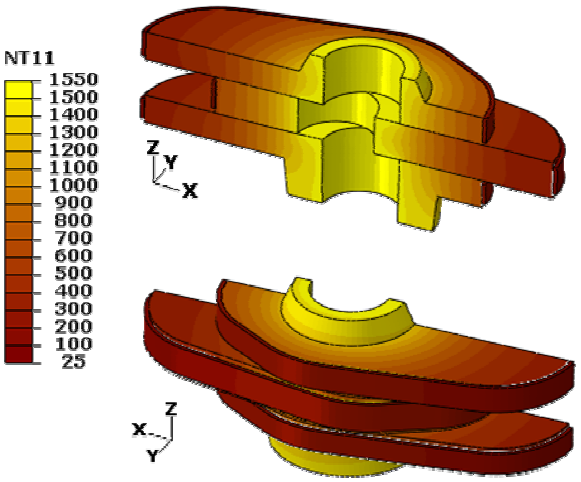


Stress (Pa)

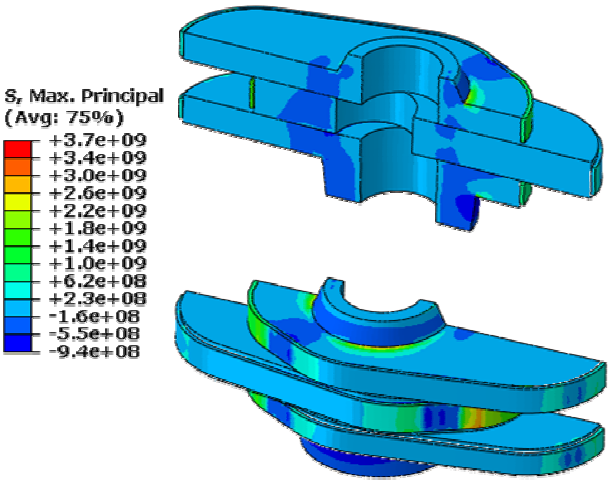


Thermo & Mechanical Behavior of Continuous Casting Step

Temperature (°C)



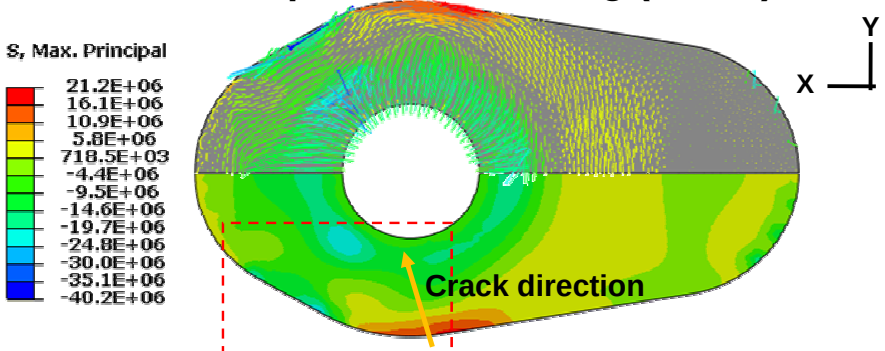
Stress (Pa)



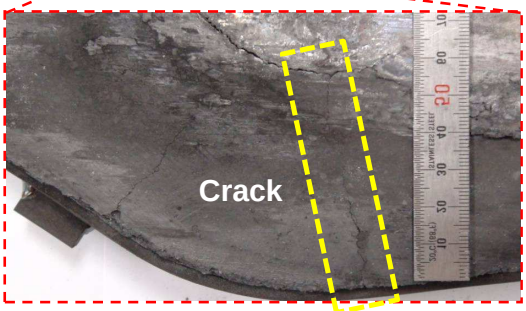
Common Through-Thickness Crack Formation Mechanism – Tensile Stress

Middle section of middle plate, Pre-heating (750°C), 502 sec

Stress Distribution (Direction & Magnitude)



Photograph of used plate



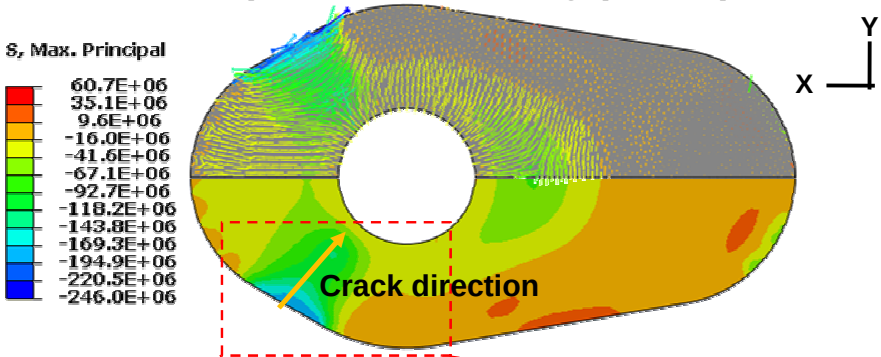
Compressive strength ≈ 245 Mpa

Tensile Strength ≈ 12 Mpa

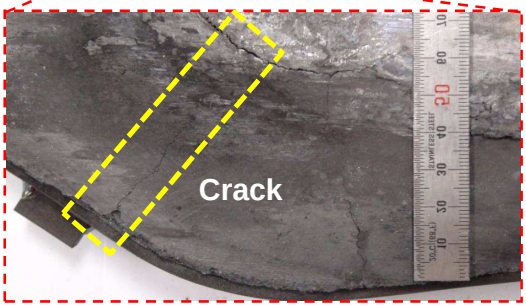
Common Through-Thickness Crack Formation Mechanism – Compressive Stress

Middle section of middle plate, Pre-heating (750°C), 12600 sec

Stress Distribution (Direction & Magnitude)



Photograph of used plate



Compressive strength ≈ 245 MPa

Conclusion

- **During preheating step, tensile and compressive stresses exceed tensile and compressive strength**
  → Crack location matches prediction

- **If cracks are already formed in preheating step, different stress and temperature distributions will result**

Future Work

- **Creep and residual stress behavior is needed to better investigate cracks in sliding gate**
- **Thermal-stress simulation should extend after preheating**
- **Cassette design is needed for exact deformation and pressure to plates**
- **UTN and SEN design is needed for knowing contact region**

References

[1] Korea Gas Safety Corporation
[2] Varun Kumar Singh, B.G. Thomas, CCC Annual report 2010, UIUC, August 12, 2010
[3] Incropera, F.P., and Dewitte, P.D., 2002, *Fundamentals of Heat and Mass Transfer*, John Wiley and Sons, New York
[4] *"New Generation Ladle Slide Gate System for Performance Improvement"*, J. Chaudhuri, 2007
[5] *"Thermal Loading of Periclase Plates in Sliding Gates of Steel-teeming Ladles",* K. V. Simonov, 1980
[6] Chosun Refractories Co. Ltd. Research Center
[7] Monarch Instrument, "*Table of Total Emissivity*"

Acknowledgements

- Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Tata Steel, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech, POSCO, SSAB, ANSYS-Fluent)
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