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Thermal Stress Cracking of Sliding Gate Plates

POSTECH

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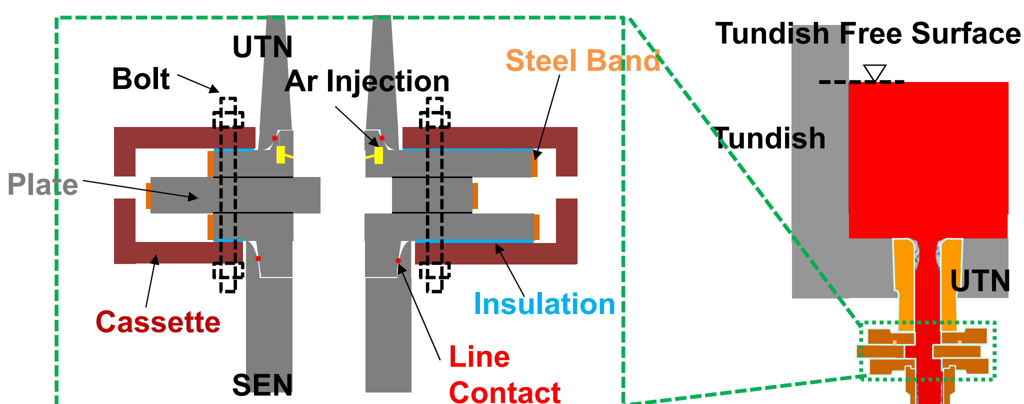
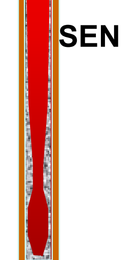
Research Background

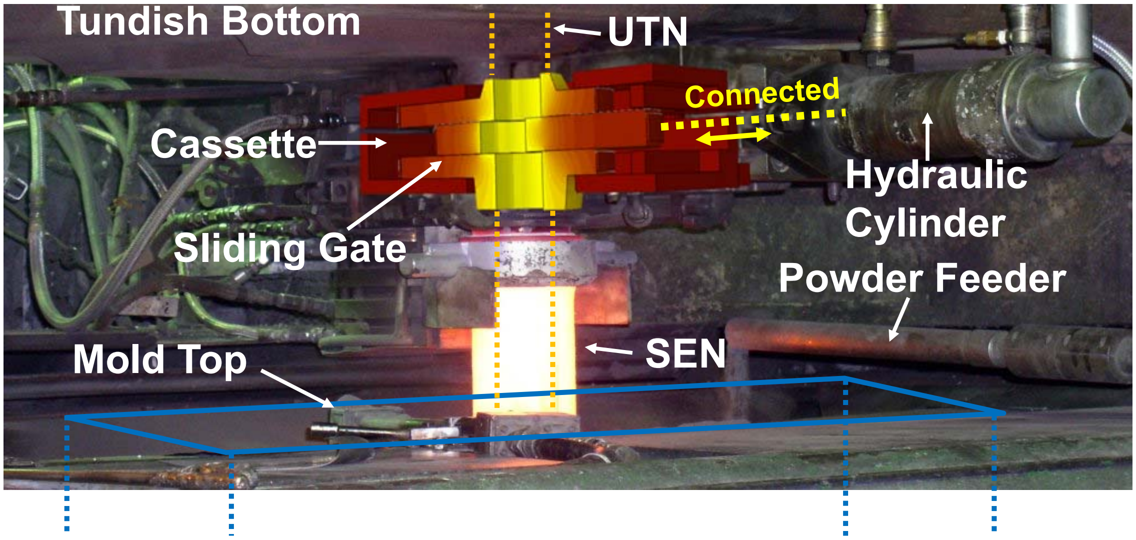




Schematic of Sliding Nozzle System

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

Sliding Gate Operation in Plant [1]



Plant Temperature Measurement	Preheating	Casting
Ambient Air (Thermometer)	~100℃	~120℃
Cassette Surface (Pyrometer)	~200℃	~270℃

Type of Cracks

Bottom view of used plate & common cracks

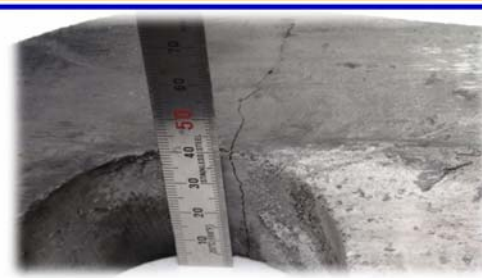


Photo of common through-thickness crack

Schematic of rare cracks locations

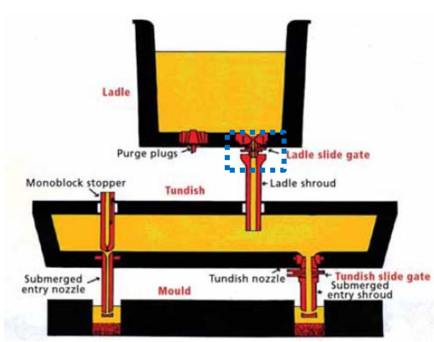
Cross section view of common crack

* Refractory component: 85% Alumina, 7% Zirconia, 8% Graphite [2]

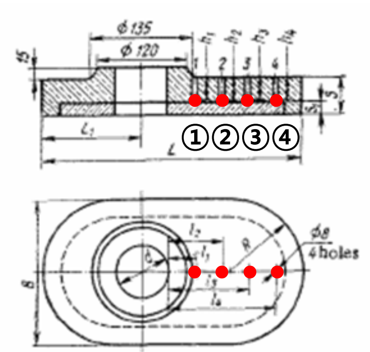
Possible Mechanisms of Common Crack Formation

- **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

Model Validation Problem – Ladle Plate Heating



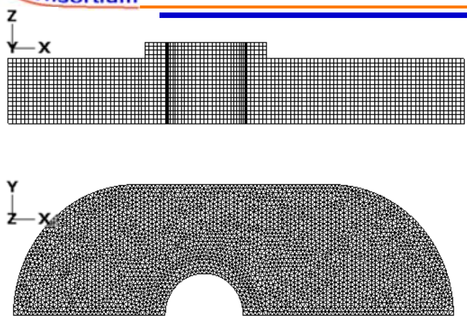
Schematic of casting equipment [3]



Location of thermocouples in plate[4]

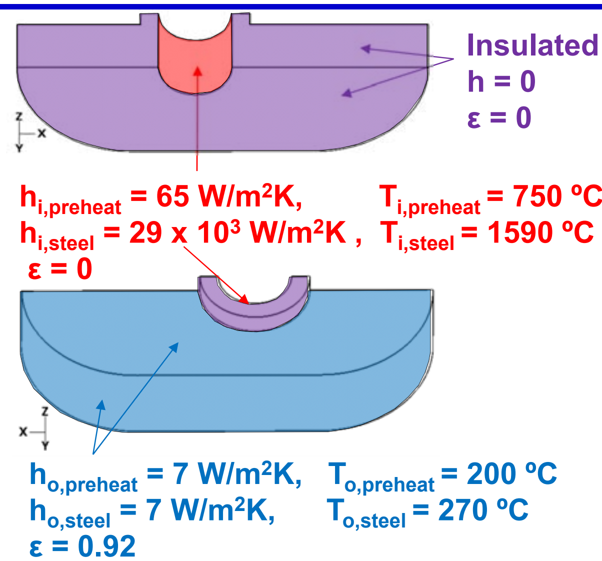
- Ladle plate temperature was measured during top teeming of molten steel into mold
- 4 Thermocouples were installed on upper plate
- Plates were subjected to heat treatment at 170 °C [4]

Heat Transfer Model Validation: Ladle-Plate Heating Problem



Part	Elements
Ladle Plate	(Wedge) 92,378

Finite element mesh



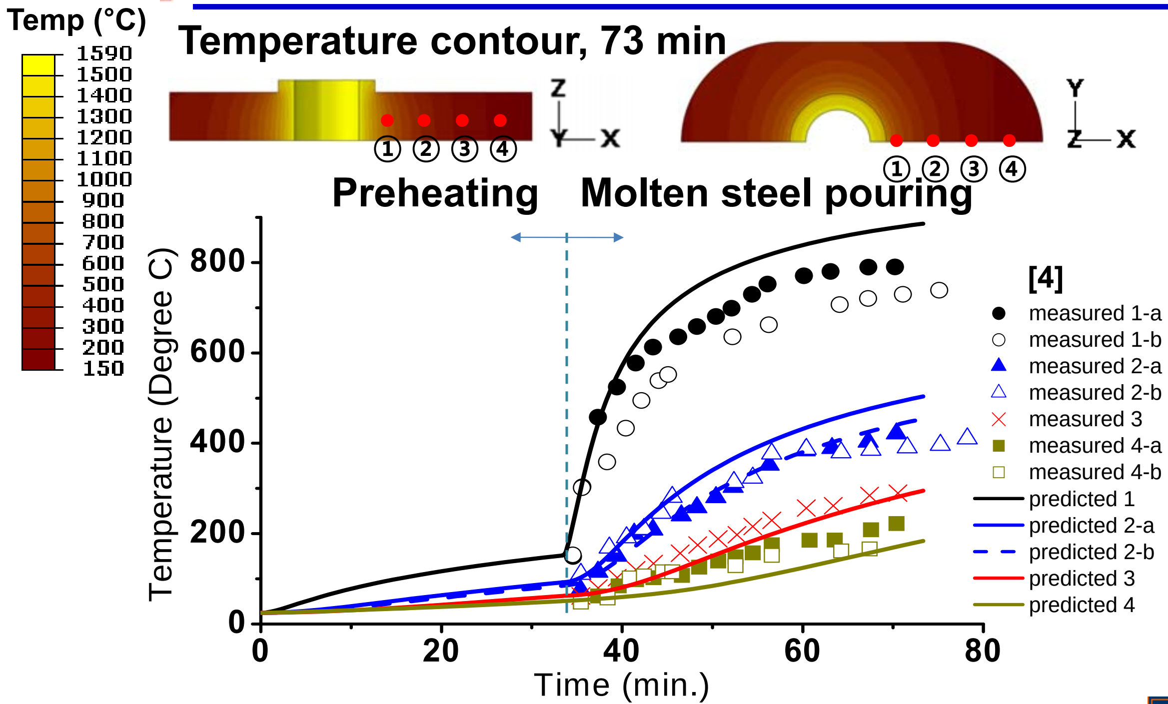
Boundary conditions

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

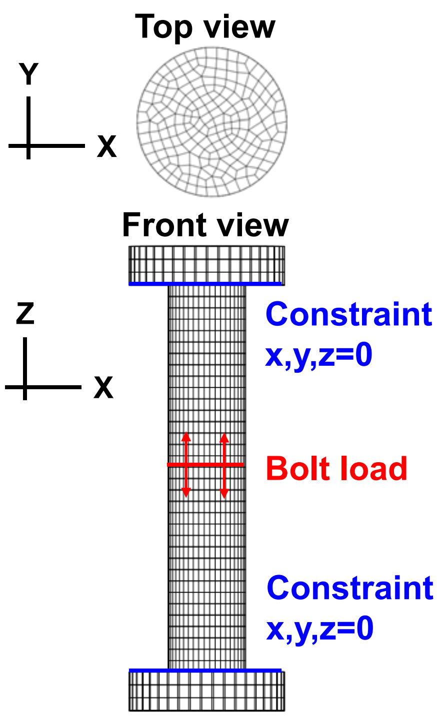
Properties for Ladle Plate Model Validation Problem

		Symbol	Value	Units
	Initial Nozzle Temperature	$T_{initial}$	25	°C
Preheating [5]	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	$T_{o,preheat}$	200	°C
	External Convection Heat Transfer Coefficient (Free)	$h_{o,preheat}$	7	W/m²·K
Casting [5]	Molten Steel Temperature	$T_{i,steel}$	1550	°C
	Internal Convection Heat Transfer Coefficient (Forced)	$h_{i,steel}$	28719.63	W/m²·K
	External Ambient Temperature	$T_{o,steel}$	270	°C
	External Convection Heat Transfer Coefficient (Free)	$h_{o,steel}$	7	W/m²·K
	Density [2]	ρ	3200	kg/m³
	Thermal Conductivity [2]	k	8.26	W/m·K
	Specific Heat [2]	C_p	1004.64	J/kg·°C
	Stefan-Boltzmann Const.	σ	5.669×10^{-8}	W/m²·K⁴
	Emissivity [6]	ε	0.92	-

Comparison of Measured and Predicted Temperature in Ladle Plate



Conditions of Bolt-load Test Problem



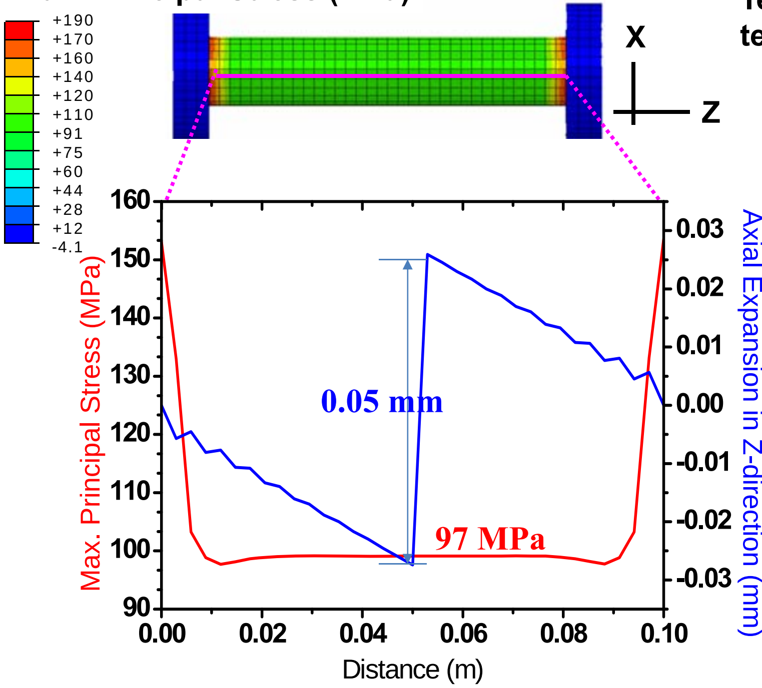
Bolt details[7]

Bolt Friction, μ	*0.3* --
Bolt Thread Pitch, λ	*1.5 mm*
Bolt Tightening Torque, τ	*100 N-m*
Bolt Diameter, d	*20 mm*
Bolt Length, L	*100 mm*
Bolt Elastic Modulus, E	*200 GPa*

Axial tensile force generated in the bolt [8] ;

$$F_{bolt} = \frac{2\tau}{d}\left(\frac{\pi d - \mu\lambda}{\lambda + \pi\mu d}\right) = 30.66\ kN$$

Results of Bolt-load Test Problem



Tensile force produces axial tensile stress in the bolt ;

$$\sigma = \frac{F_{bolt}}{\pi\left(\frac{d}{2}\right)^2} = \frac{30.66\ kN}{\pi\left(\frac{20\ mm}{2}\right)^2}$$

$$= 97\ MPa$$

This pre-stress corresponds to axial expansion of;

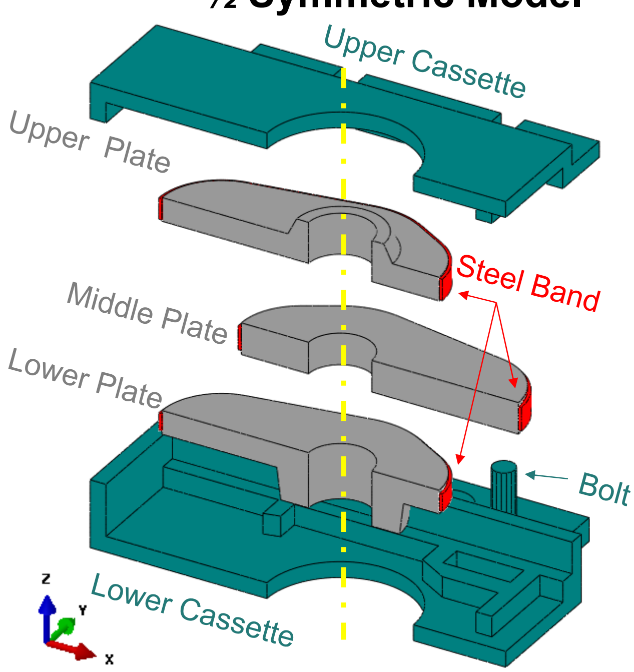
$$\Delta L = \frac{\sigma L}{E} = \frac{97\ MPa \times 100\ mm}{200\ GPa}$$

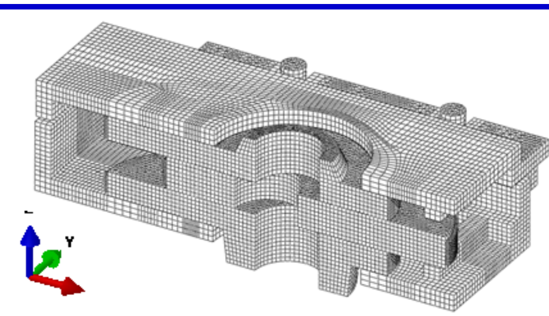
$$= 0.05\ mm$$

<u>well-matched!!!</u>

Tundish Sliding Gate Nozzle Component / Finite Element Mesh

½ Symmetric Model





	Hex.	Wedge
Upper Plate	-	14,122
Middle Plate	-	17,016
Lower Plate	-	18,122
Upper Band	6,356	-
Middle Band	6,750	-
Lower Band	4,972	-
Upper Cassette	6,945	3,510
Lower Cassette	16,763	8,438
Total	102,994	

Properties for Tundish Sliding Gate Model

		Symbol	Value	Units
Refractory (Plates) [2,5]	Density	ρ_{ref}	3200	kg/m^3
	Elastic modulus	E_{ref}	65×10^9	Pa
	Poisson's ratio	ν_{ref}	0.2	-
	Thermal Conductivity	k_{ref}	8.26	W/m·K
	Specific Heat	$C_{p,ref}$	1004.64	J/kg·°C
	Expansion coefficient	α_{ref}	8.2×10^{-6}	$°C^{-1}$
Steel (Bands, Cassette) [2,5]	Density	ρ_{steel}	7860	kg/m^3
	Elastic modulus	E_{steel}	206×10^9	Pa
	Poisson's ratio	ν_{steel}	0.3	-
	Thermal Conductivity	k_{steel}	48.6	W/m·K
	Specific Heat	$C_{p,steel}$	418.6	J/kg·°C
	Expansion coefficient	α_{steel}	1.78×10^{-5}	$°C^{-1}$
Stefan-Boltzmann Const.		σ	5.669×10^{-8}	$W/m^2 \cdot K^4$
Emissivity [6]		ε_{ref}	0.92	-
		ε_{steel}	0.75	-

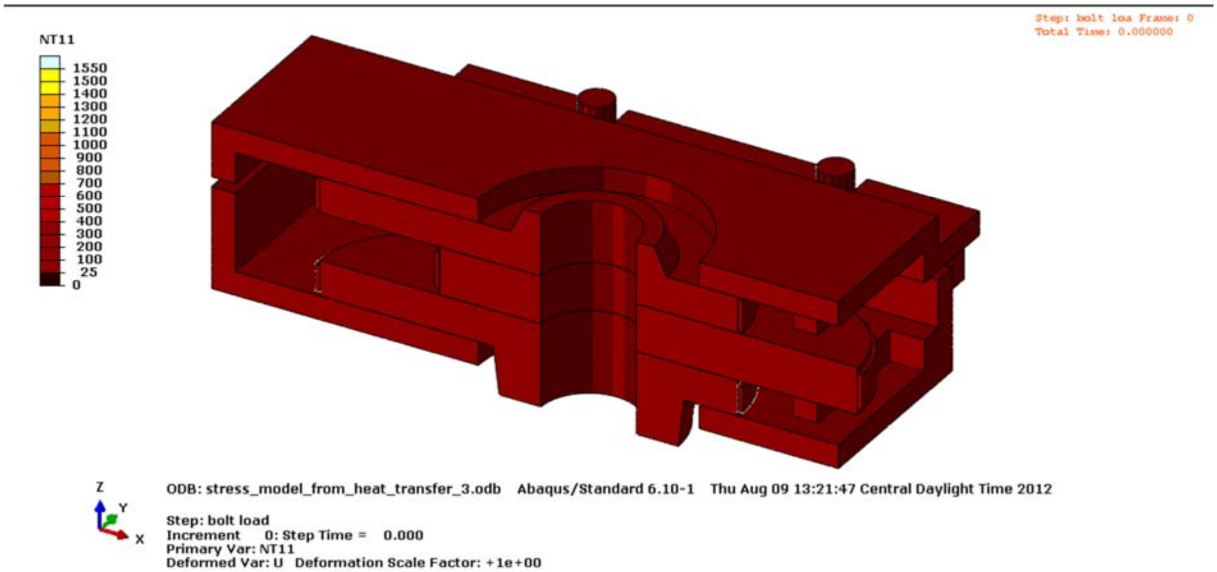
Variables and Boundary Conditions for Tundish Sliding Gate Model

		Symbol	Preheating	Tundish Filling	Casting	Cooling	Units
Opening Ratio		-	100	0	60	-	%
Duration Time		t	210	12.5	210	267	min.
Initial Temperature		$T_{initial}$	25	-	-	-	°C
Internal Sink Temperature		T_i	750 (Gas)	1550 (Molten Steel)	1550 (Molten Steel)	25	°C
Internal Convection Heat Transfer Coefficient (Forced)		h_i	65	29×10^3	29×10^3	7	$W/m^2 \cdot K$
External Ambient Temperature	Inside of Cassette area	$T_{o,in}$	200	270	270	25	°C
	Outside of Cassette area	$T_{o,out}$	100	120	120	25	°C
External Convection Heat Transfer Coefficient (Free)		h_o	7	7	7	7	$W/m^2 \cdot K$

- **Mechanical Contact**
  "surface to surface contact"
  between steels, $\mu=0.3$ [7]
  between refractories, $\mu=0.1$ [2]
  between steel and refractory, $\mu=0.45$ [9]
- **Symmetry**
  middle section(X-Z plane) of all parts

Thermal Behavior (Movie)

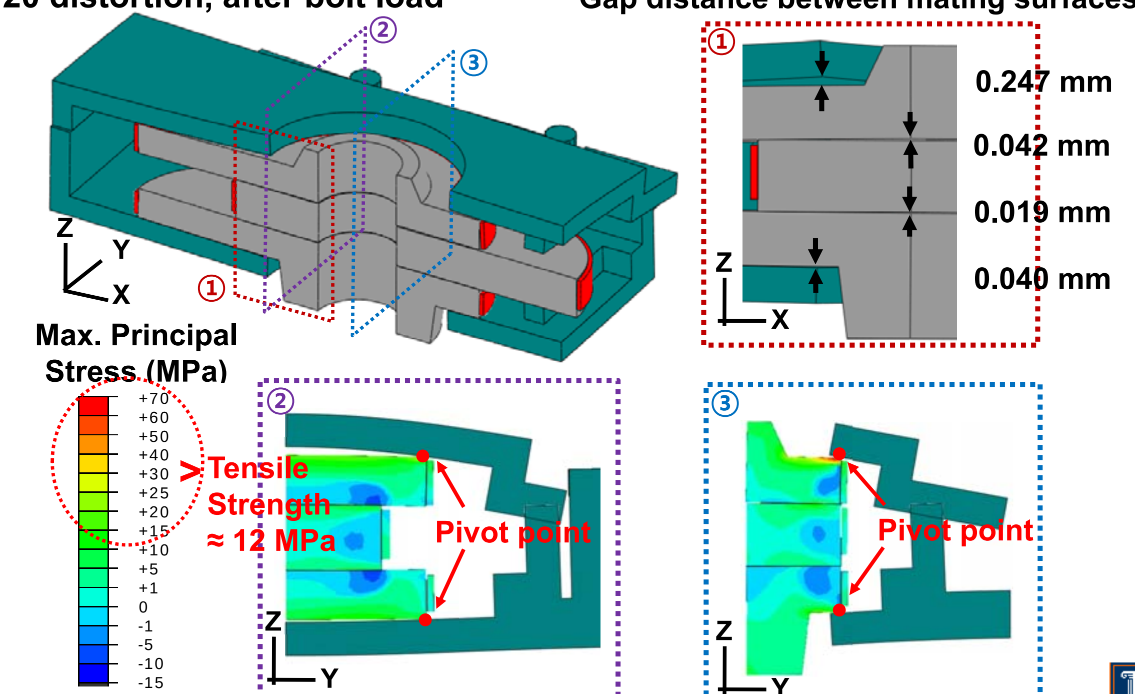
Temperature (˚C)



Bending Effect Induced by Bolted Cassette

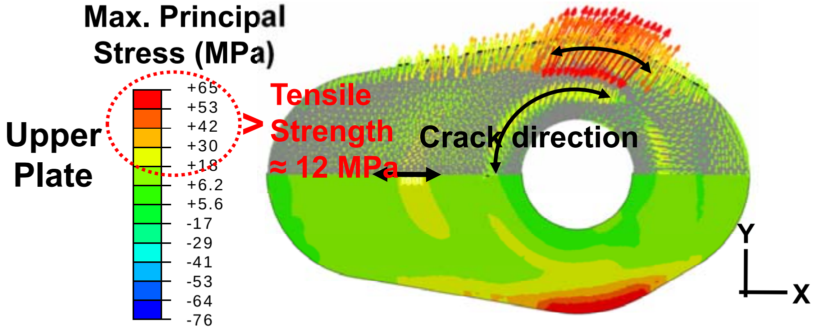
x 20 distortion, after bolt load

Gap distance between mating surfaces



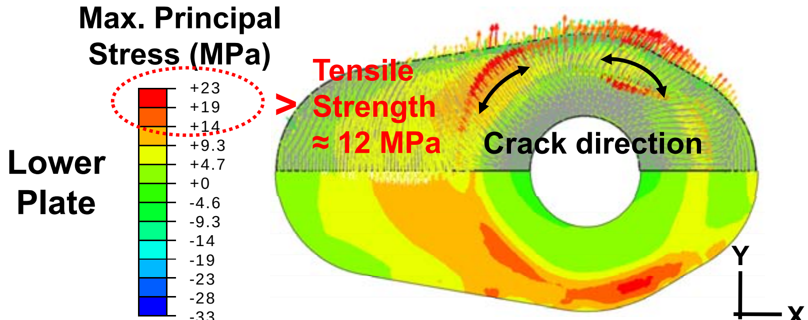
Bending Effect
Tensile Stress on Upper/Lower Plate

Section view of 2.5 mm lower surface from upper plate top, Only bolt load applied



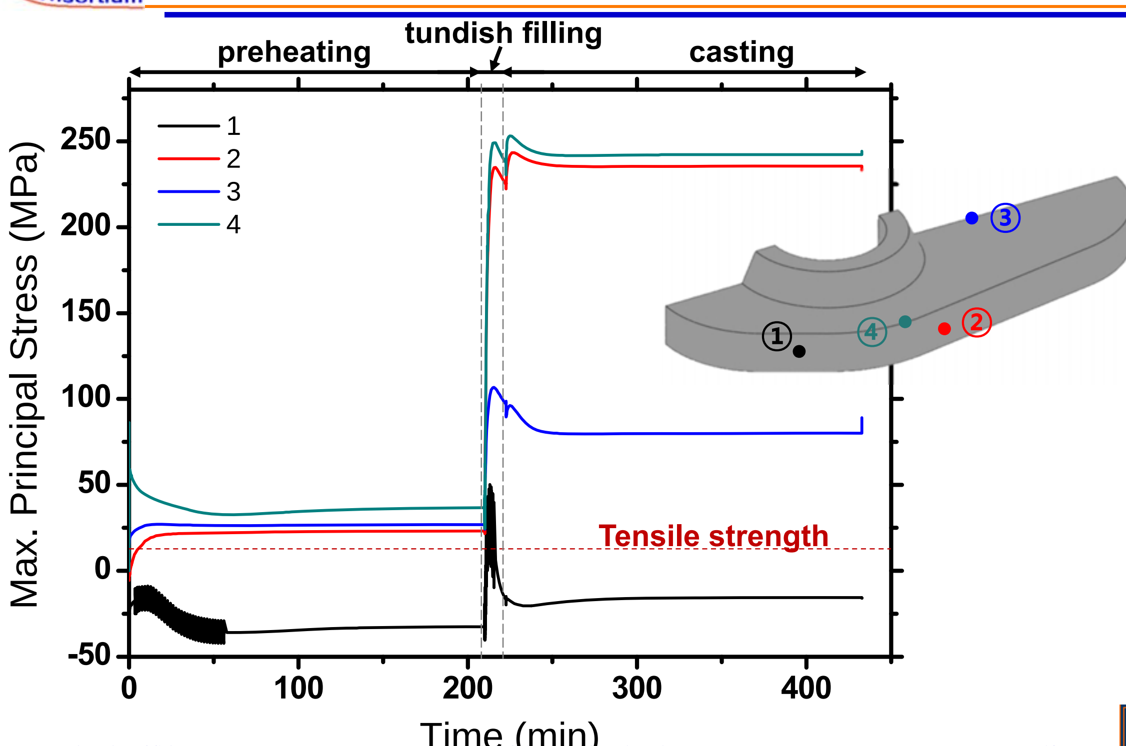
Larger bending of upper cassette forms higher tensile stress around upper plate edge

Section view of 2.5 mm upper surface from lower plate bottom, Only bolt load applied

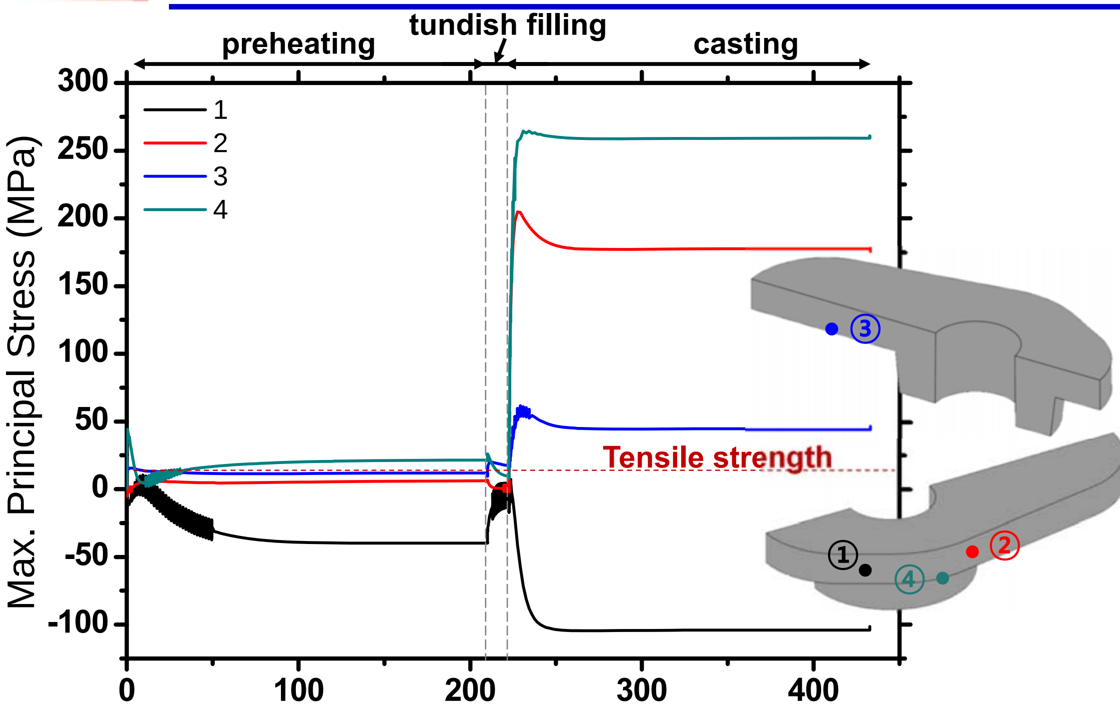


Cassette bending is effected on crack formation in circular direction

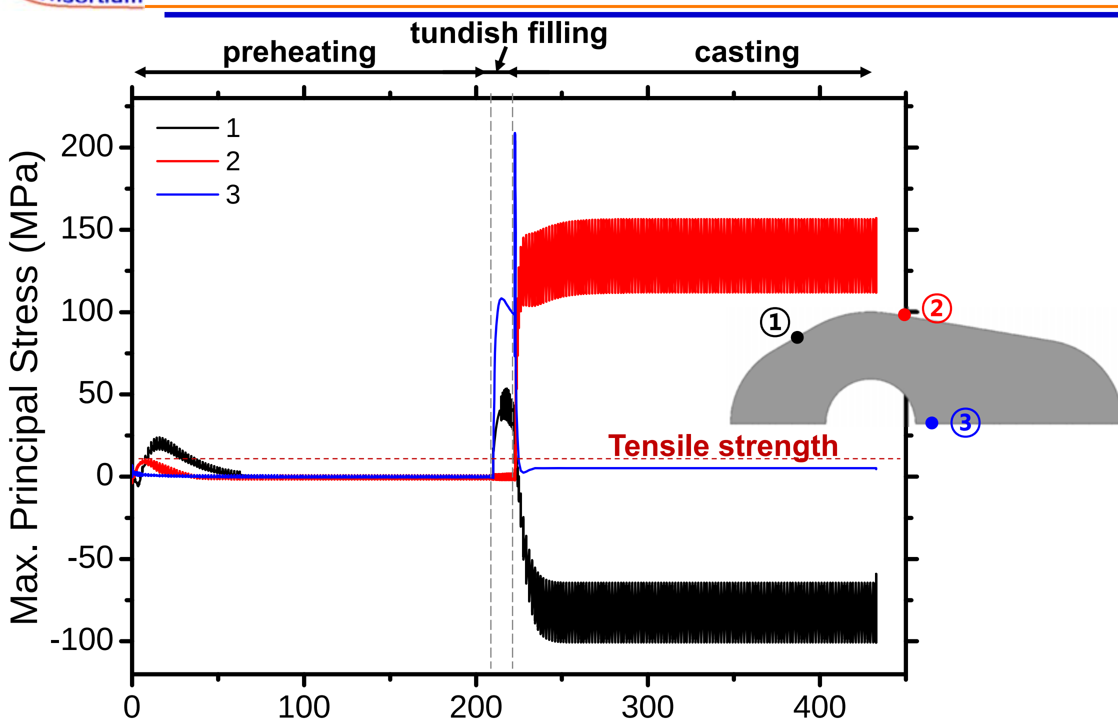
Predicted Stress Profile of Upper Plate



Predicted Stress Profile of Lower Plate



Predicted Stress Profile of Middle Plate



Common Through-thickness Crack Formation Mechanism – Middle Plate (Preheating)

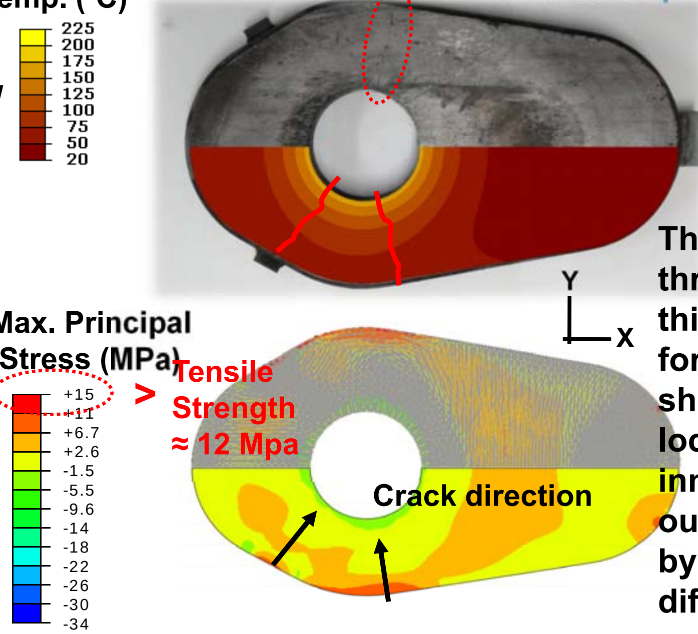
Middle section view of middle plate, 461 sec. of preheating stage

Temp. (˚C)

Photograph of Used Plate/ Temperature Contour

Max. Principal Stress (MPa)

Stress Distribution (Direction & Magnitude)



These common through-thickness cracks form in the shortest distance location between inner bore and outside caused by temperature difference

Rare Crack Formation Mechanism Middle Plate (Tundish Filling)

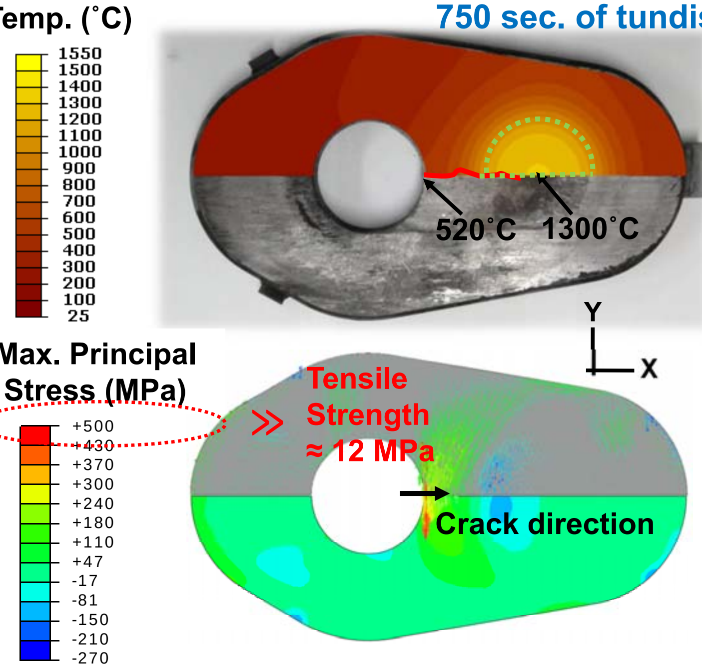
Section view of 10 mm lower surface from middle plate top, 750 sec. of tundish filling stage

Temp. (˚C)

Temperature Contour/ Photograph of Used Plate

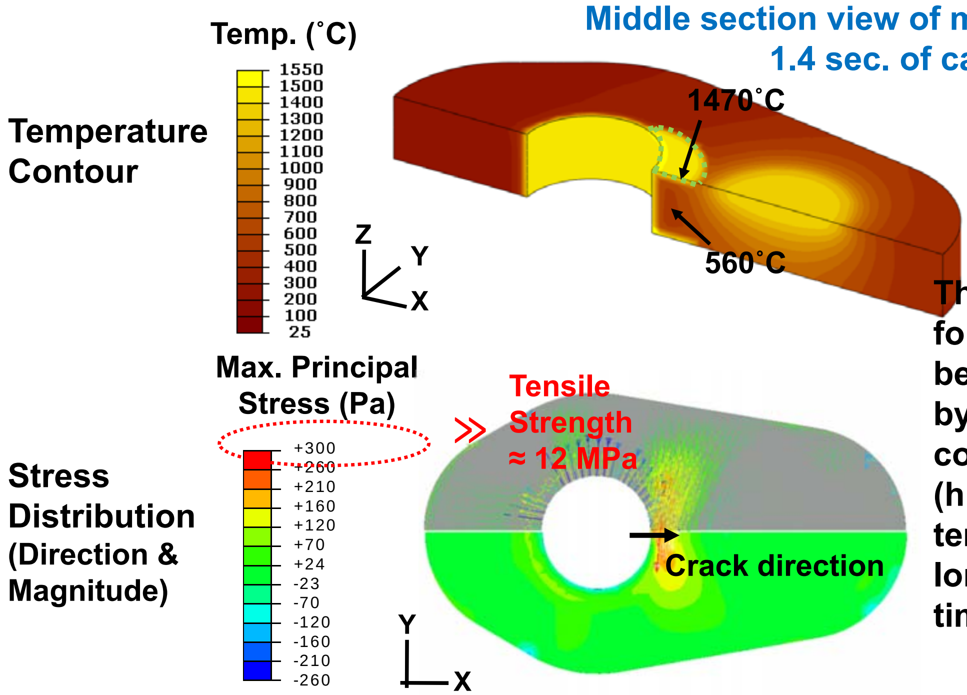
Max. Principal Stress (MPa)

Stress Distribution (Direction & Magnitude)



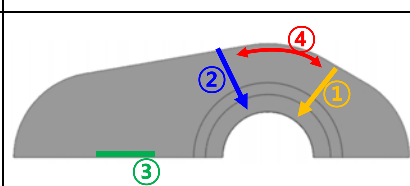
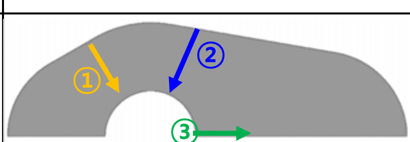
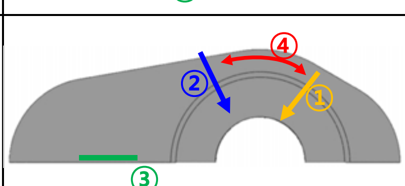
This rare crack formation can be controlled by preheating conditions (higher flame temperature, longer preheat time)

Rare Crack Formation Mechanism Middle Plate (Casting)



This rare crack formation can be controlled by preheating conditions (higher flame temperature, longer preheat time)

Summary of Crack Formation

Y X	Crack Location/direction	#	Max. Principal Stress (MPa)			
			Bolt Load	Preheat	Tundish Filling	Casting
Upper Plate		1	-20	-40	50	-20
		2	-5	20	230	240
		3	20	25	110	80
		4	65	35	250	250
Middle Plate		1	0	25	50	-80
		2	0	12	0	130
		3	0	0	100	5
Lower Plate		1	-10	-40	-10	-100
		2	0	5	0	200
		3	10	10	15	60
		4	50	20	20	270

Importance of Creep Effect

Creep measurements in ceramic [10]

$$\dot{\varepsilon}_{creep} = A\sigma^n \exp\left(\frac{-Q}{RT}\right)$$

A ; constant
σ ; applied stress
n ; stress exponent
Q ; activation energy
R ; universal gas constant, 1.99 cal/K·mol
T ; absolute temperature, 1723 K

[10]	Al_2O_3 (%)	SiO_2 (%)	Fe_2O_3 (%)	*A*	*σ* (MPa)	*n*	*Q* (kcal/mol)	ε_{creep}
BP Mullite	75.5	24.0	0.2	6.67×10^{-3}	0.4	0.6	70	**1.47×10^{-6}**
HF 17	78.2	21.6	0.1	6.05×10^{17}	0.4	0.9	223	**16.02×10^{-6}**
ZED FM	78.5	20.9	0.1	3.79×10^{9}	0.4	0.7	152	**320.40×10^{-6}**

$$\varepsilon_{el} = \frac{\sigma}{E} = \frac{0.4\ MPa}{65\ GPa} = 6.15 \times 10^{-6}$$

Creep effect is important, but depends greatly on material

Further work is needed to determine the properties, and to add to the model

Conclusion

- **Bended cassette induced by bolt load forms unexpected tension on upper/lower plate**
- **Tensile stress is the most important factor to cause cracks formation on plates(compressive stress do not exceed compressive strength)**
- **Common through-thickness cracks induced by big temperature difference are unavoidable → Gradual flame temperature increment will be good for preheating stage**
- **Rare crack formation on middle plate can be controlled by preheating conditions (higher temperature, longer preheating time)**

References

[1] POSCO, Technical Research Lab., Steelmaking Research Group
[2] Chosun Refractories Co. Ltd. Research Center
[3] J. Chaudhuri, et. al., *"New Generation Ladle Slide Gate System for Performance Improvement,"* 2007
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