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Thermomechanical Behavior of Continuous Casting Funnel Molds

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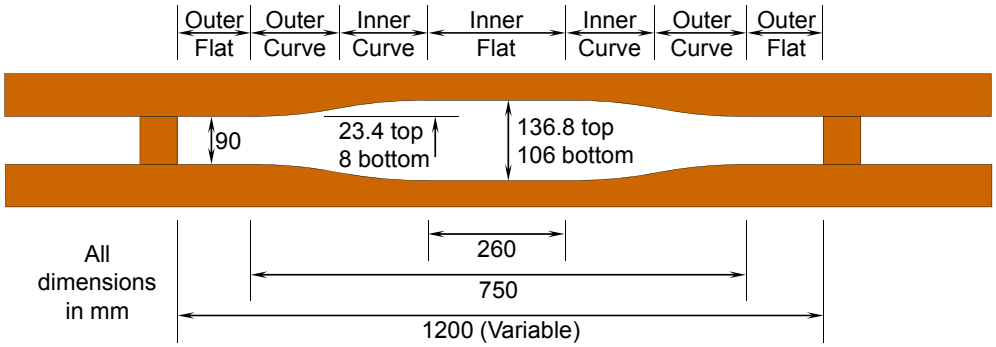
Objectives

- Explore the thermal and mechanical response of the mold plates to the heat load experienced during regular casting, using a steady-state elastic nonlinear finite-element model
- Validate with plant measurements
- Recommend adjustment to taper to account for mold thermal distortion

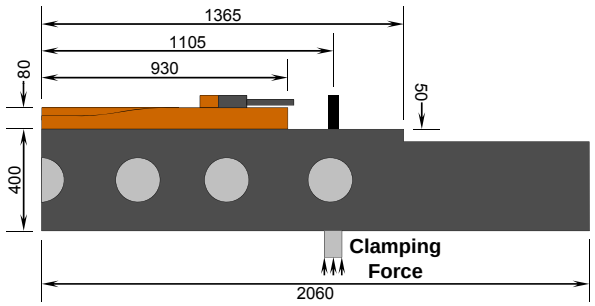
Funnel Mold Geometry

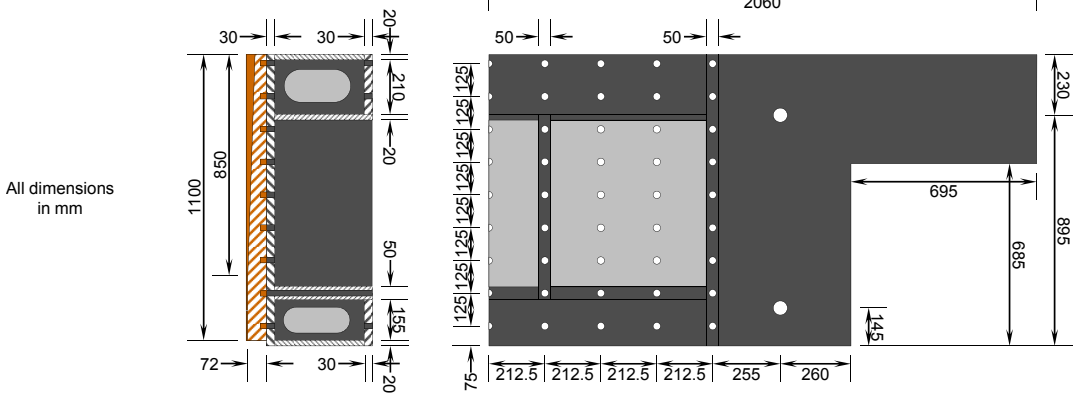


- Cu-Cr-Zr alloy
  - 350 W/(m·K) thermal conductivity
  - 8900 kg/m³ mass density
  - 385 J/(kg·K) specific heat capacity
  - 117 GPa Young's modulus, 0.181 Poisson's ratio
- No coating layers

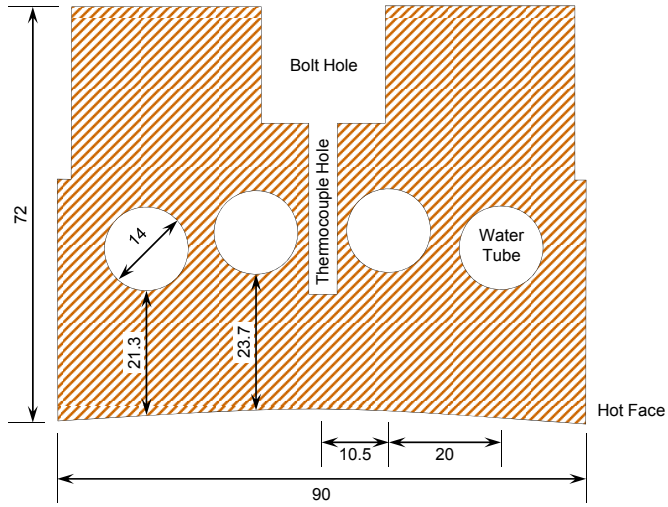
Water Box Geometry

- 316 stainless
  - 200 GPa Young's modulus
  - 0.3 Poisson's ratio

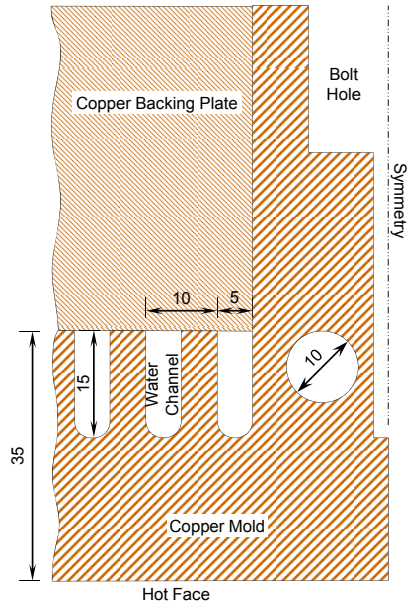




Water Channel Geometry



Narrow face



Wide face

Mathematical Thermal-Stress Model

Isotropic Fourier heat conduction $k\,\nabla^2 T = 0$

Mechanical equilibrium without body forces $\nabla \cdot \boldsymbol{\sigma} = 0$

Hooke's law $\boldsymbol{\sigma} = \boldsymbol{C} : \boldsymbol{\varepsilon}^{el}$

Isotropic linear elasticity $C_{ijk\ell} = \dfrac{E}{2(1+\nu)}\left(\delta_{ik}\delta_{j\ell} + \delta_{i\ell}\delta_{jk}\right) + \dfrac{\nu E}{(1+\nu)(1-2\nu)}\delta_{ij}\delta_{k\ell}$

Strain decomposition $\boldsymbol{\varepsilon}^{el} = \boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{th}$

Thermal strain tensor $\boldsymbol{\varepsilon}^{th} = \alpha\left(T - T_0\right)\boldsymbol{I}$

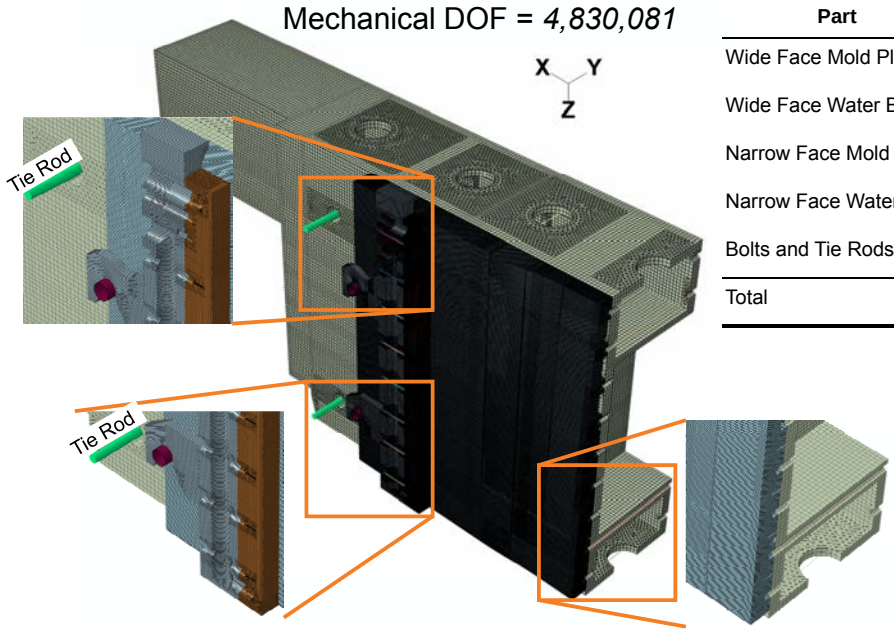
Linearized total strain tensor $\boldsymbol{\varepsilon} = \frac{1}{2}\left(\nabla \boldsymbol{u} + \left(\nabla \boldsymbol{u}\right)^T\right)$

Employ the finite element method to solve the boundary-value problem

Finite Element Mesh

Thermal DOF = *1,089,166*

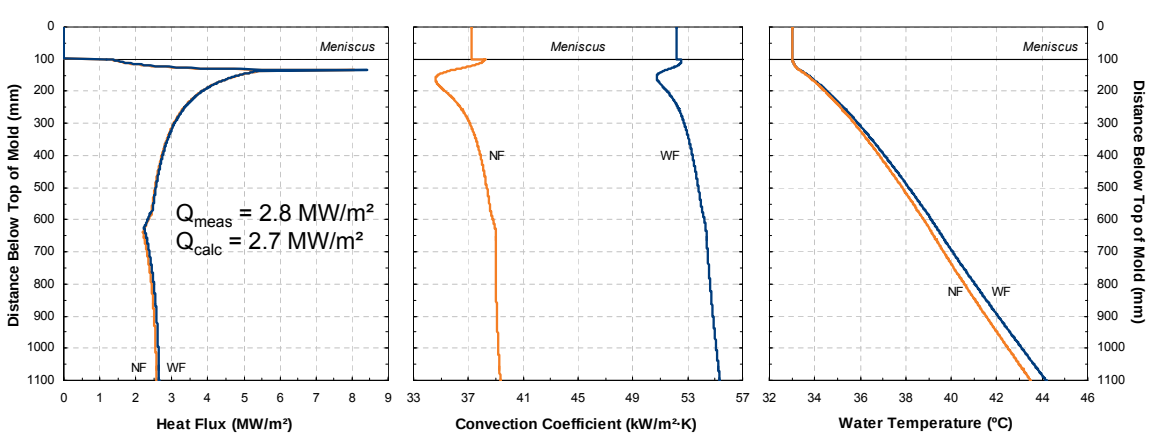
Mechanical DOF = *4,830,081*



Part	Nodes	Elements
Wide Face Mold Plate	855,235	4,223,072
Wide Face Water Box	185,534	190,457
Narrow Face Mold Plate	233,931	495,566
Narrow Face Water Box	83,269	239,604
Bolts and Tie Rods	110	55
Total	1,358,081	5,148,754

Thermal Boundary Conditions

- Specified heat flux on mold hot faces $-k\,\nabla T\cdot\boldsymbol{n}=\boldsymbol{q}^{sp}\cdot\boldsymbol{n}$
- Convection BC on water channels $-k\,\nabla T\cdot\boldsymbol{n}=h\left(T-T_{\infty}\right)$
- All other faces thermally insulated $-k\,\nabla T\cdot\boldsymbol{n}=0$
- Values calculated from CON1D calibrated to plant measurements [Santillana *et al.*, ISIJ Int. 2008]

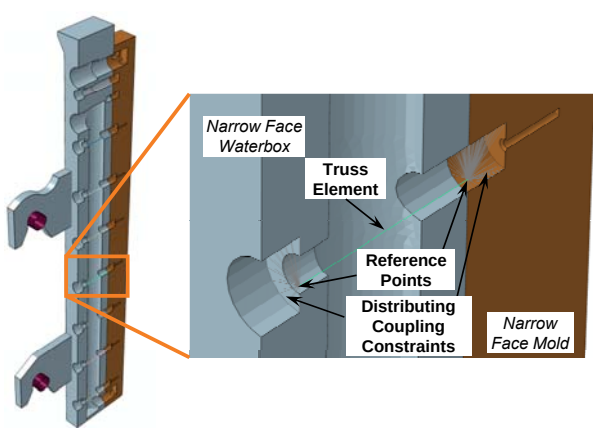


Mechanical Boundary Conditions

- Ferrostatic pressure on hot faces $p = \rho g z$
- Symmetry on appropriate planes $\boldsymbol{u} \cdot \boldsymbol{n} = 0$
  - Wide face mold and waterbox centerline
  - Narrow face mold and waterbox centerline
  - Tie rod centerlines
- Mechanical contact on mating faces
  - "Hard" contact algorithm within ABAQUS
  - Copper-copper coefficient of static friction μ = 1.0 [-]
  - Copper-steel coefficient of static friction μ = 0.5 [-]

Mold Bolts and Tie Rods

Bolt	Length (mm)	Cross-Sectional Area (mm²)	Applied Torque (N·m)	Pre-Load (kN)	Pre-Stress (MPa)	Stiffness (MN/m)
NF (Short)	150	181	100	30	168	240
WF Short	87	187	100	30	162	424
WF Long	449	143	100	30	212	63
Upper Tie Rod	1335	1215	--	40	33	34.8
Lower Tie Rod	1335	1215	--	70	58	33.4

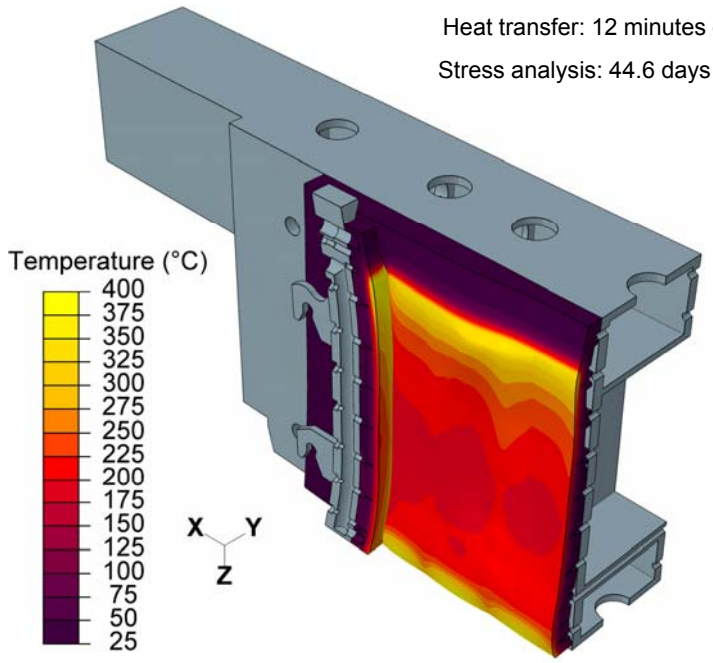


- Bolts modeled as truss elements and prestressed according to plant practice
  - See [Thomas *et al.*, Iron and Steelmaker 1998]
- "Distributing coupling constraints" tie bolt ends to surfaces on mold pieces
- Simulated tie rods account for actual tie rods and spring packs

Simulation Results

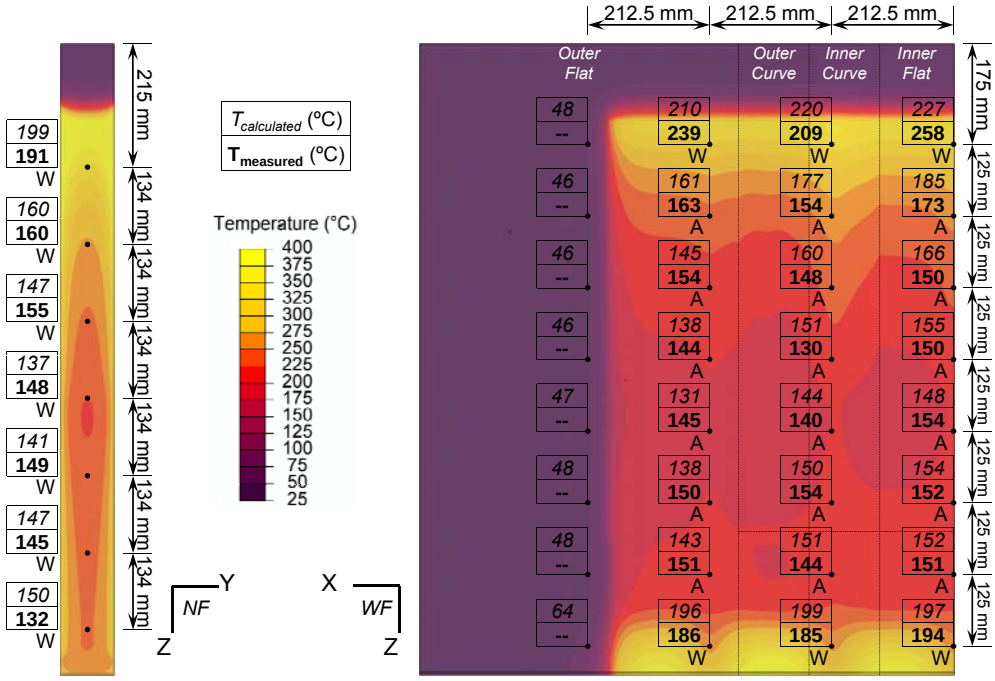
Heat transfer: 12 minutes on 8-core 2.66 GHz Intel Xeon

Stress analysis: 44.6 days on 8-core 2.66 GHz Intel Xeon



50× scaled distortion

Thermocouple Validation



Measured Thermocouple Adjustment

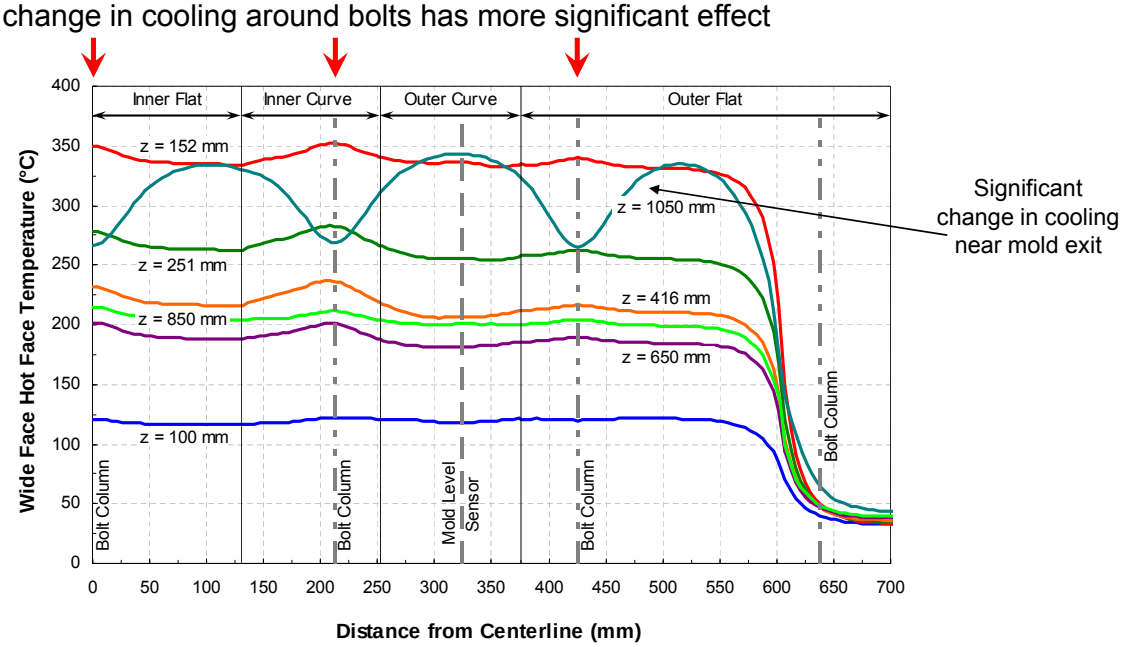
- To account for heat removal along thermocouples:

$$T'_{TC} = T_{TC} + \left(T_{TC} - T_{amb}\right)\frac{d_{gap}}{k_{gap}}\frac{\sqrt{hDk_{TC}}}{D/2}$$

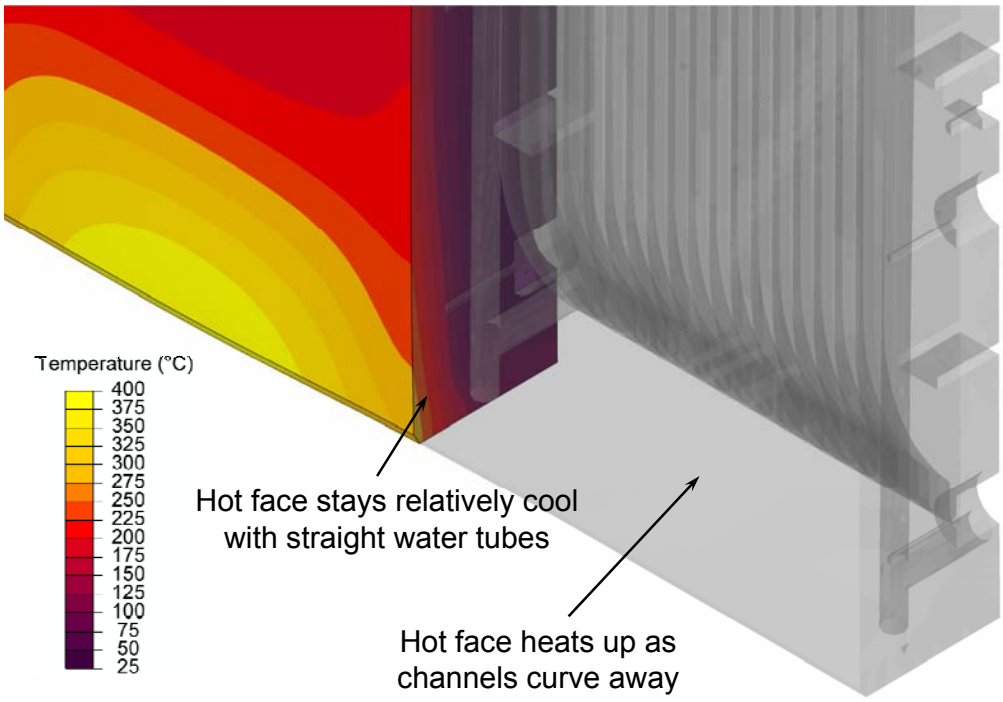
T'_{TC}	Adjusted TC temperature
T_{TC}	Actual TC temperature
T_{amb}	Ambient temperature, 25 ºC or local water temperature
d_{gap}	Gap between copper and TC, 0.01 mm
k_{gap}	Thermal conductivity of gap, 1.25 W/(m·K)
k_{TC}	Thermal conductivity of thermocouple, 212 W/(m·K)
D	Diameter of thermocouple wire, 4 mm
h	Convection coefficient, 5 kW/(m²·K) for water or 0.1 kW/(m²·K) for air (previous slides mark with 'W' and 'A' which are adjusted for which)

Wide Face Temperature Profiles

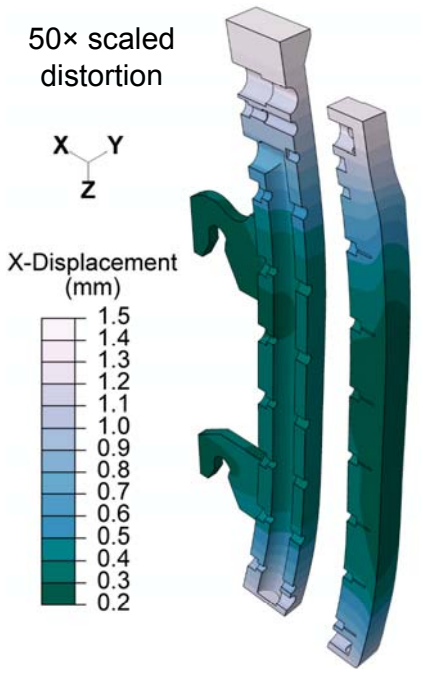
Slight 2D heat transfer in funnel region (less than 2 ºC), but change in cooling around bolts has more significant effect

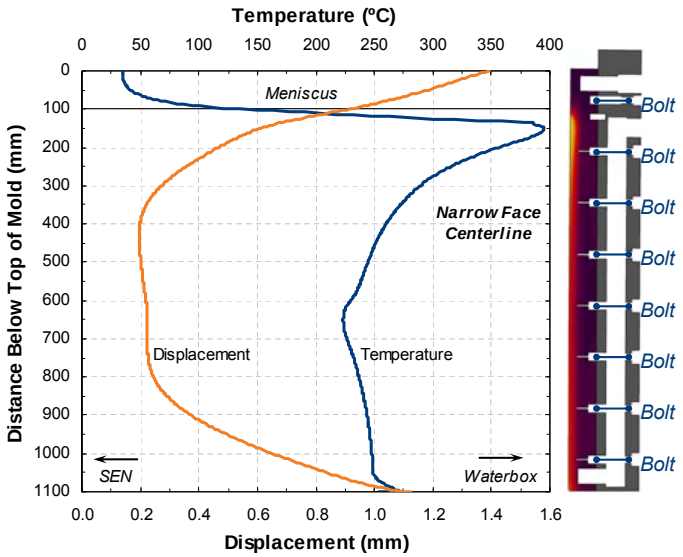


Cooling Near Mold Exit

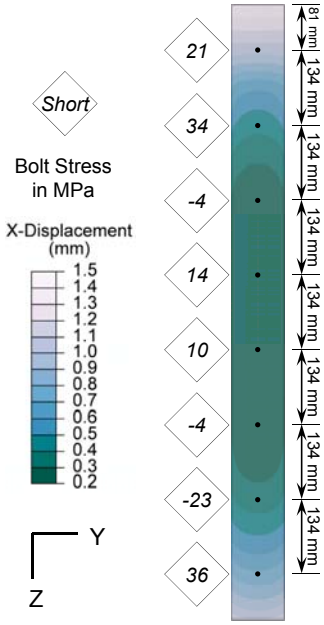


Narrow Face Distortion

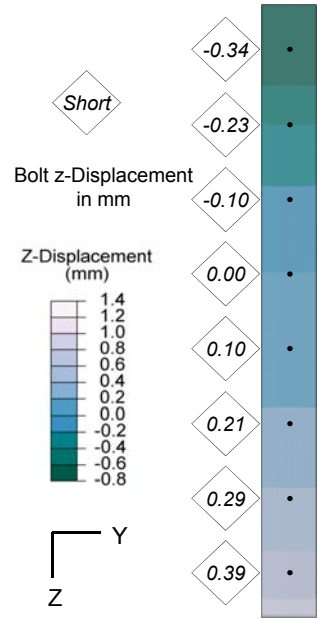




Narrow Face Distortion



Out-of-plane displacement, bolt stresses

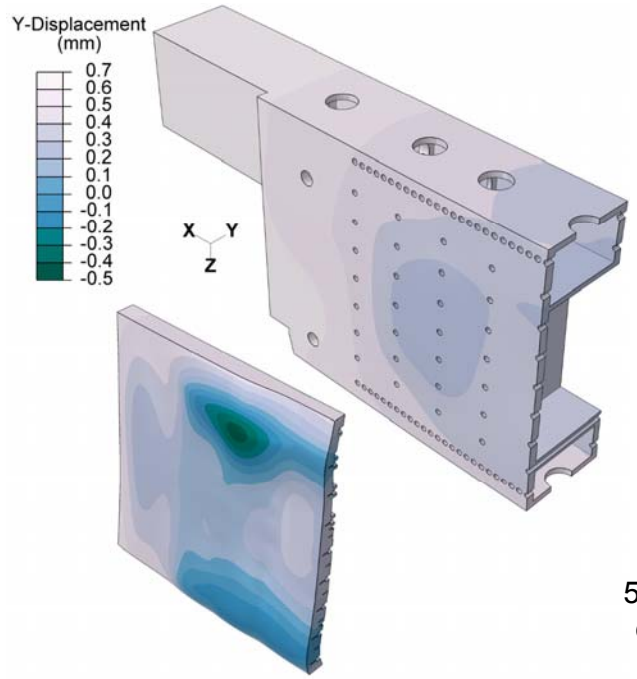


In-plane displacement, bolt displacement

Narrow Face Distortion

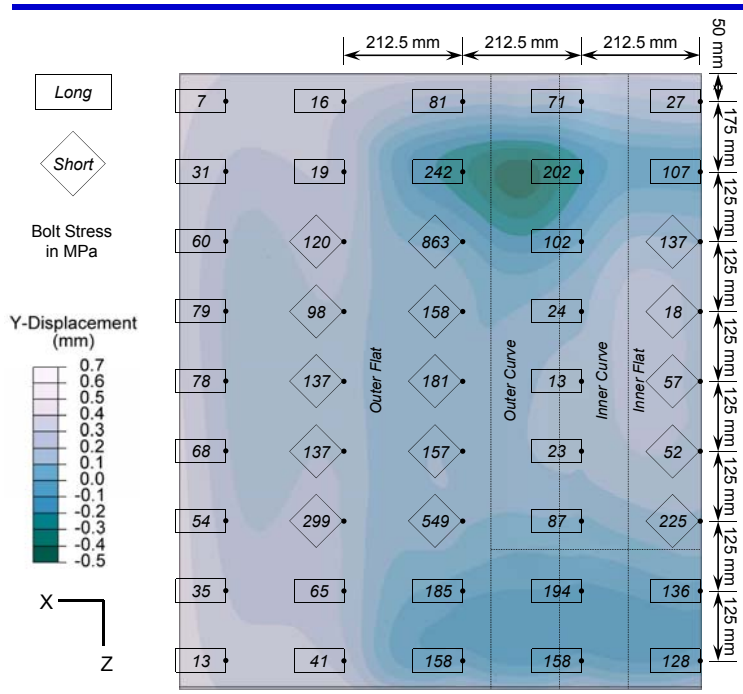
- Narrow face distorts into roughly-parabolic arc
  - Typical behavior
  - Elongates by 2 mm
- Low bolt operating stresses
  - No risk of bolt tensile failure
- Small bolt displacement at mold/waterbox interface
  - 16 mm bolts in 22 mm holes
  - No risk of mold overconstraint or bolt shearing failure
- Waterbox hooks provide extra rigidity to assembly
  - Causes wobble in distortion profile
  - Bolts near hooks do not overcome prestress

Wide Face Distortion

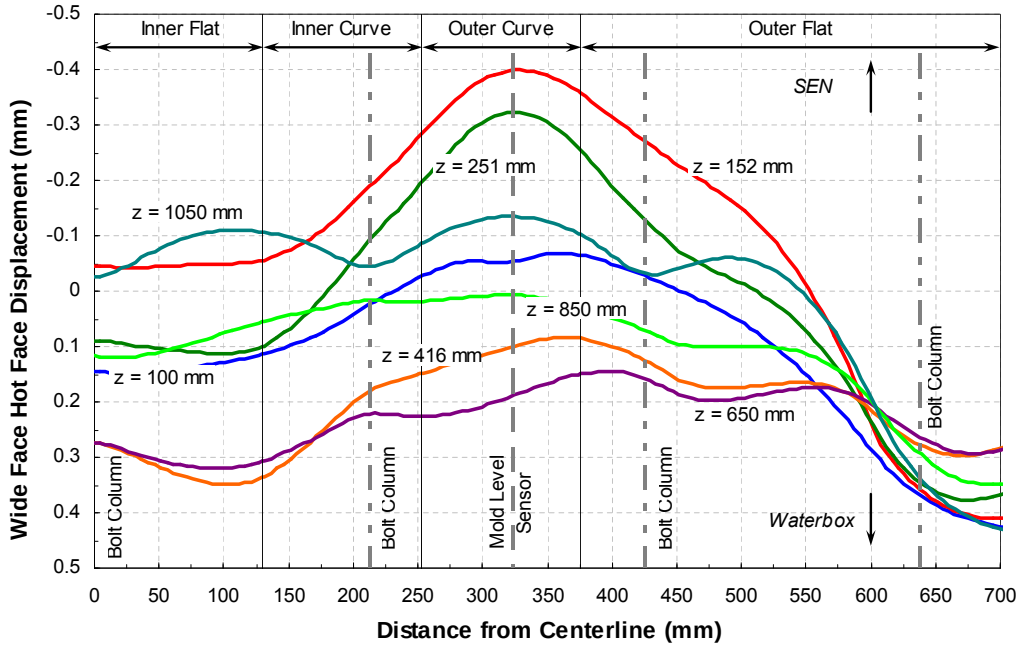


50× scaled distortion

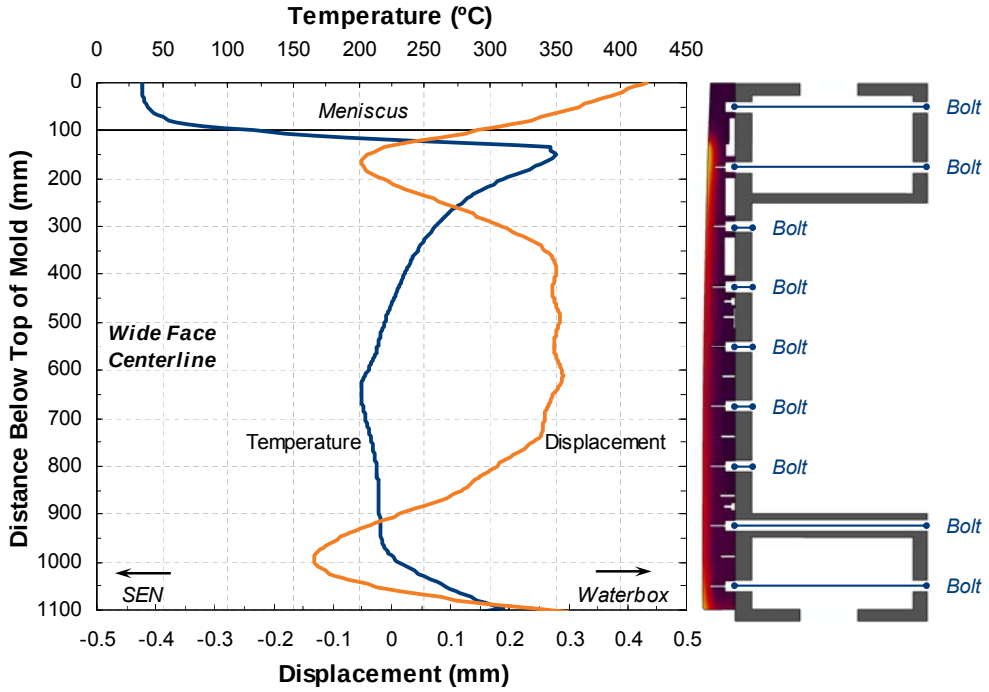
Wide Face Distortion: Out-of-Plane Behavior



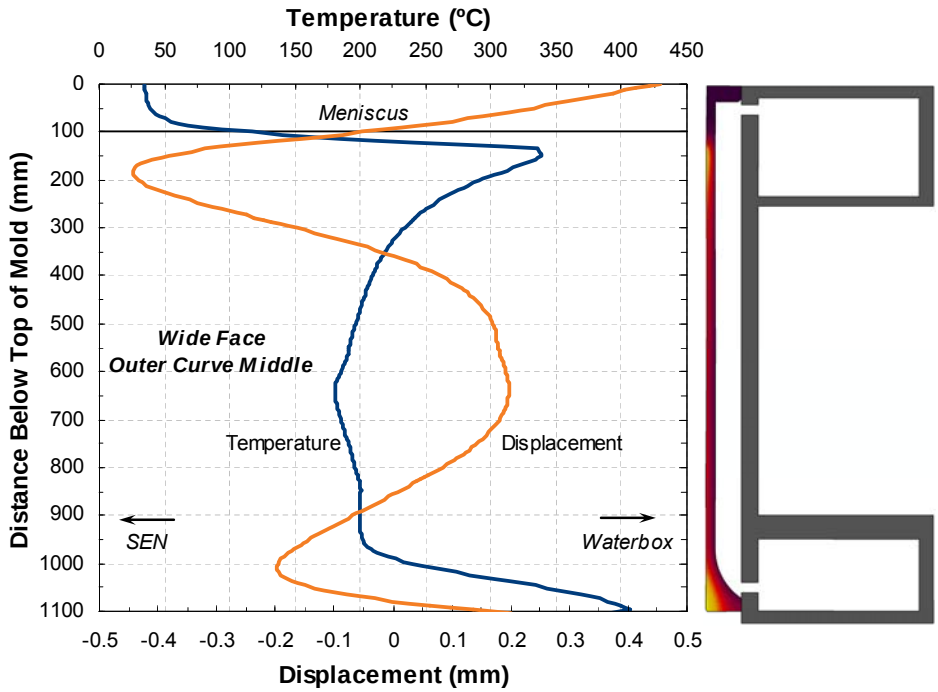
Wide Face Distortion:
Out-of-Plane Behavior



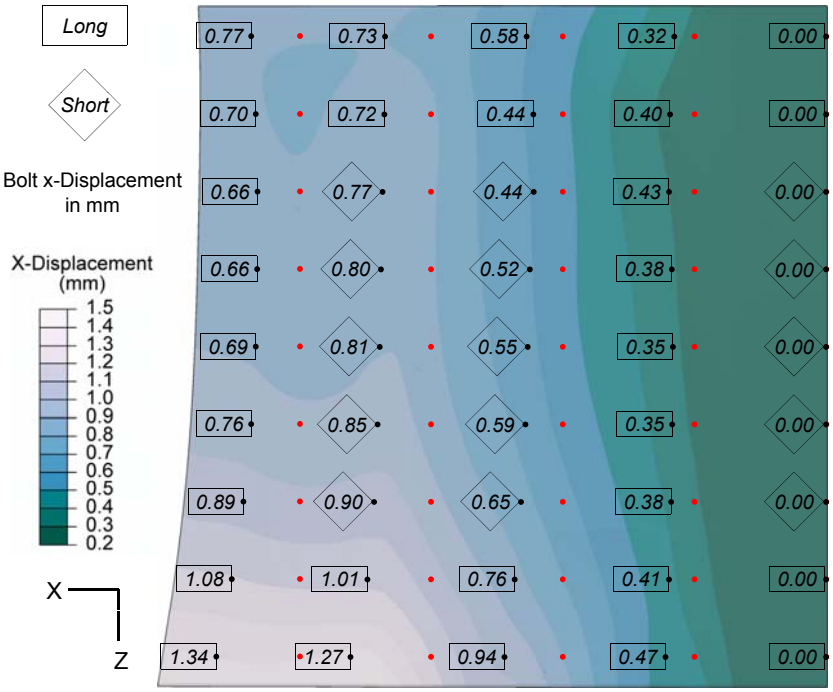
Wide Face Distortion:
Out-of-Plane Behavior at Centerline



Wide Face Distortion:
Out-of-Plane Behavior at OC Middle



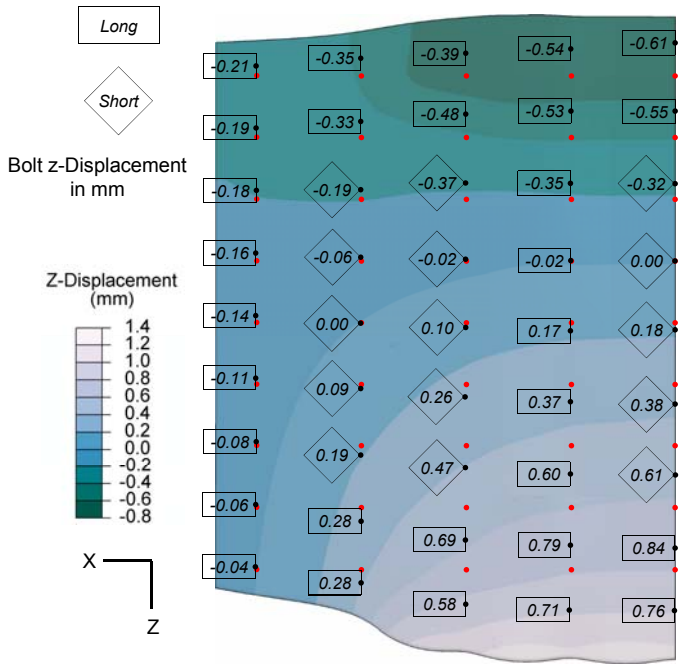
Wide Face Distortion:
In-Plane Behavior, Towards NF



100× scaled distortion in x-direction

Wide Face Distortion:

In-Plane Behavior, Towards Mold Exit



100× scaled distortion in z-direction

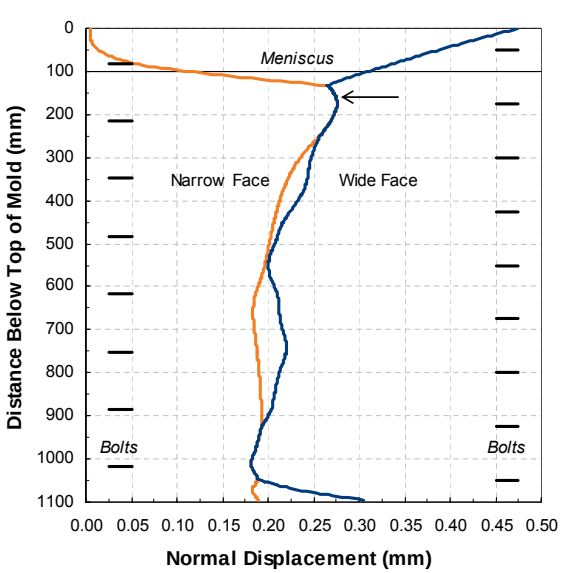
Wide Face Distortion

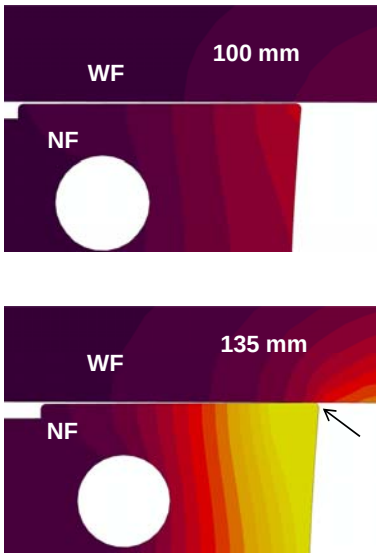
- Distorts into a ‘W’ vertically and horizontally
  - Largely because of different stiffnesses of bolts
- Distortion follows bolting pattern more than the thermal response
- Cold edges constrain against distortion
- Most severe distortion
  - Just below meniscus and just above mold exit
  - In between bolt columns

Wide Face Distortion

- Short bolts in middle regions
  - Provide most of the resistance to distortion
  - Larger bolt stresses
  - Smaller displacements of hot face
- Long bolts at top and bottom
  - Compliant bolts, not reinforced with stiffener plates
  - Lower bolt stresses
  - Larger displacements of hot face
- Small bolt displacement at mold/waterbox interface
  - 16 mm bolts in 24 mm holes
  - No risk of mold overconstraint or bolt shearing failure

Mold Interface

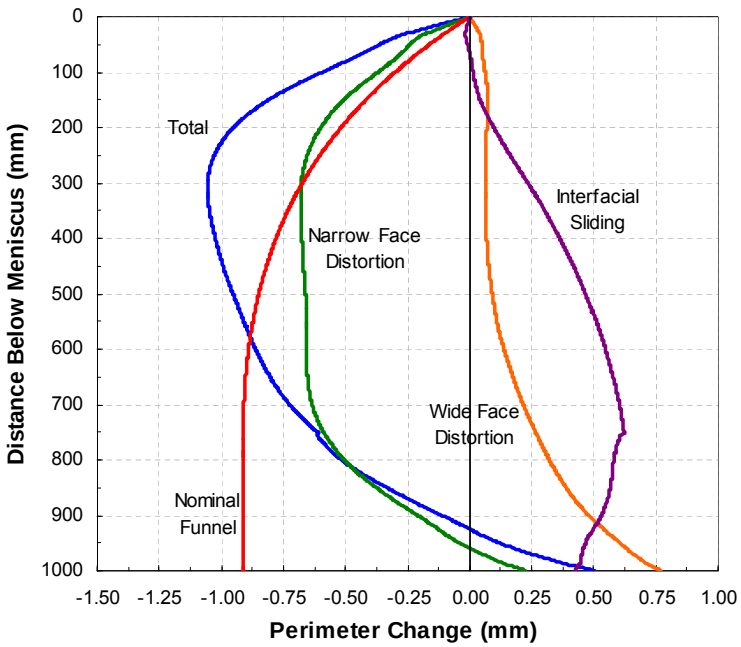




- Good contact in regions of highest temperatures
- Small gap along most of the length of the interface
- Large gap at meniscus, can fill with slag or steel and lead to “finning” defects

Effect of Distortion on Taper

- Calculate perimeter of mold as function of distance down the mold
- Contributions from
  - Funnel geometry
  - Wide face expansion
  - Narrow face distortion
  - Prevented sliding of WF relative to rigid NF
- Sliding should be considered during startup and in molds with rigidly positioned NFs

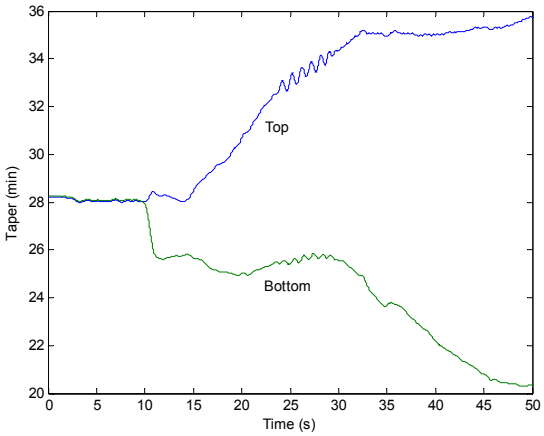


Validation

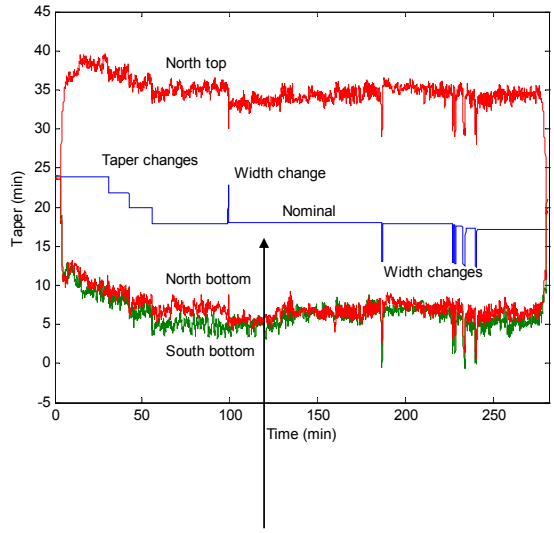
- Slopes of NF measured at top and bottom of mold with inclinometers at the Tata IJmuiden DSP
- During startup, the effect of WF expansion on NF shape must be accounted for
- During steady casting *after a width change*, the WF behavior no longer affects the shape of the NF
- Two cases to consider in calculating NF shape:
  1) "sliding" – assume rigid NF that allows WF to slide past, so "interfacial sliding contribution" to NF shape is ignored
  2) "sticking" – NF contacts and moves together with WF (due to backlash or other play-mechanisms) so the "interfacial sliding contribution" is included in NF shape

Taper Measurements

Startup (filtered)



Steady casting



After width change

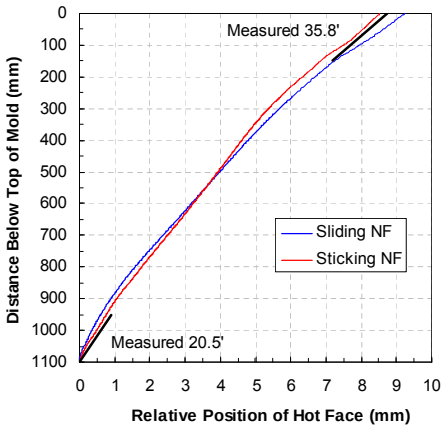
Validation

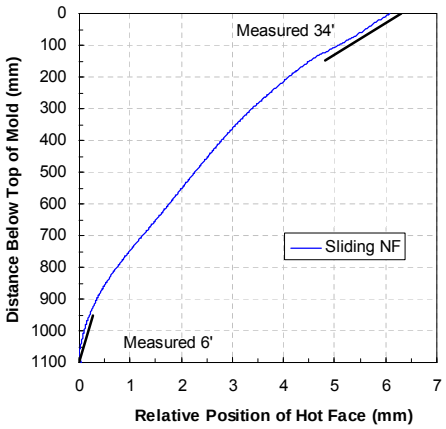
Startup

	Measured	Calculated, sliding NF	Calculated, sticking NF
Top	35.8’	39.6’	33.7’
Bottom	20.5’	14.6’	19.6’

Steady casting, after width change

	Measured	Calculated, sliding NF
Top	34’	33.2’
Bottom	6’	6.1’

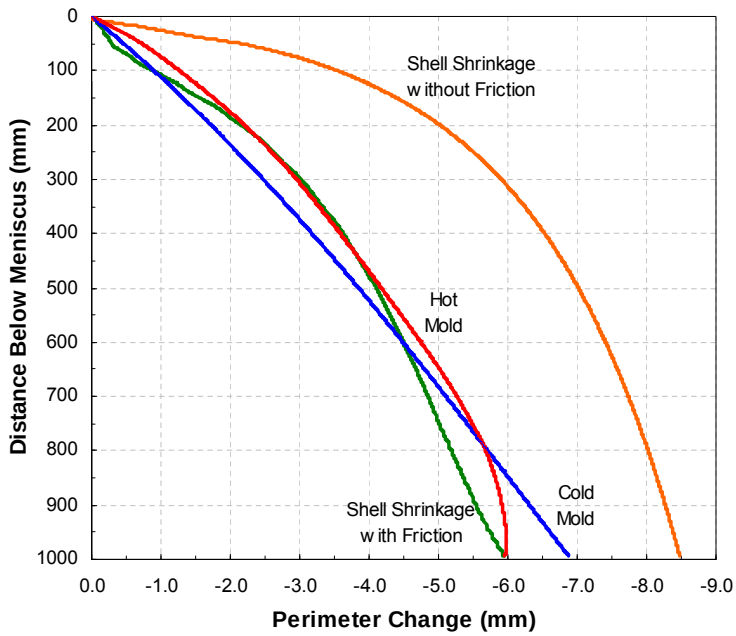




Ideal Taper?

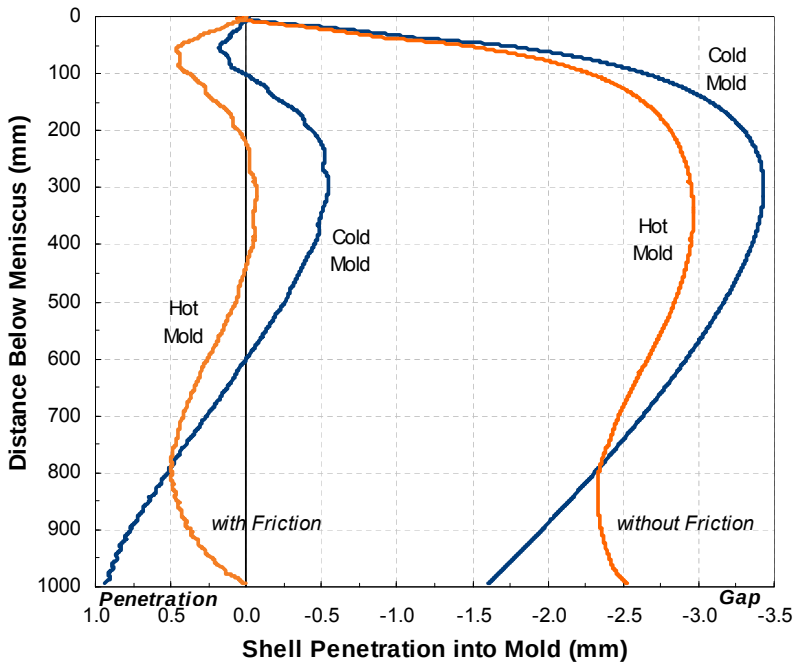
- Compare shell shrinkage from 2D thermal-stress model* of solidifying shell with Total Distortion and a 1%/m linear taper
- Shell-mold friction very important at early times
- When all effects are considered, applied taper does good job of matching shell shrinkage

- *See Hibbeler Masters Thesis for detail of the shell model



Deviation from Ideal Taper

- Shell shrinks too much = gap opens (negative numbers)
- Mold pushes too much = mold wear (positive numbers)
- Both distortion and friction *lessen* the amount of required NF taper



Mold Wear Validation

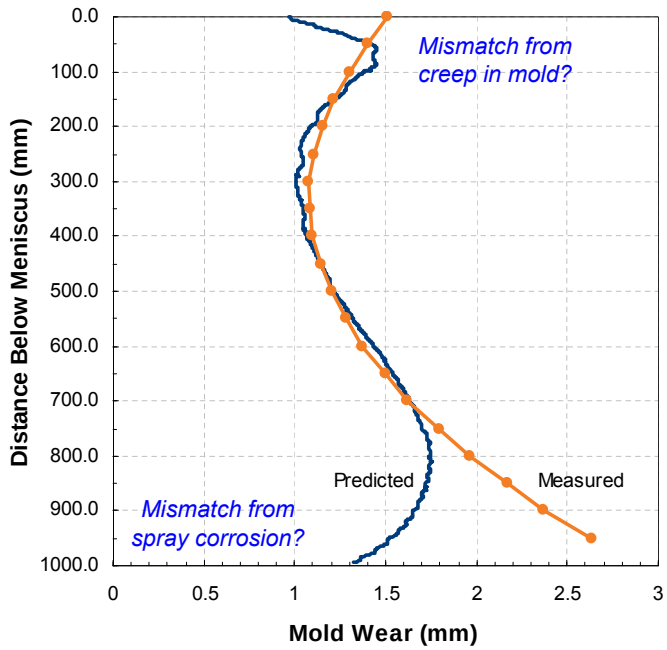
- Wear contributions:
  - "Steady" wear
  - Ferrostatic pressure
  - Distortion effects

$$W = c_0 + c_p \rho g z + d(z)$$

- Fitting constants:

$$c_0 = 0.97\,\text{mm}$$

$$c_p = 5 \cdot 10^{-6} \frac{\text{mm}}{\text{Pa}}$$



Mold Distortion Conclusions

- Constructed large 3D thermal-stress model of a funnel mold and its water box
- Narrow face shows typical distortion behavior
- Wide face distortion complicated due to widely varying constraint from different bolts
- No operational problems with bolts due to distortion
- Possible fin defect problems
- Localized distortion causes regions of excessive wear (validated by measurements) below meniscus and near mold exit
  - Can lead to shell buckling and cracks

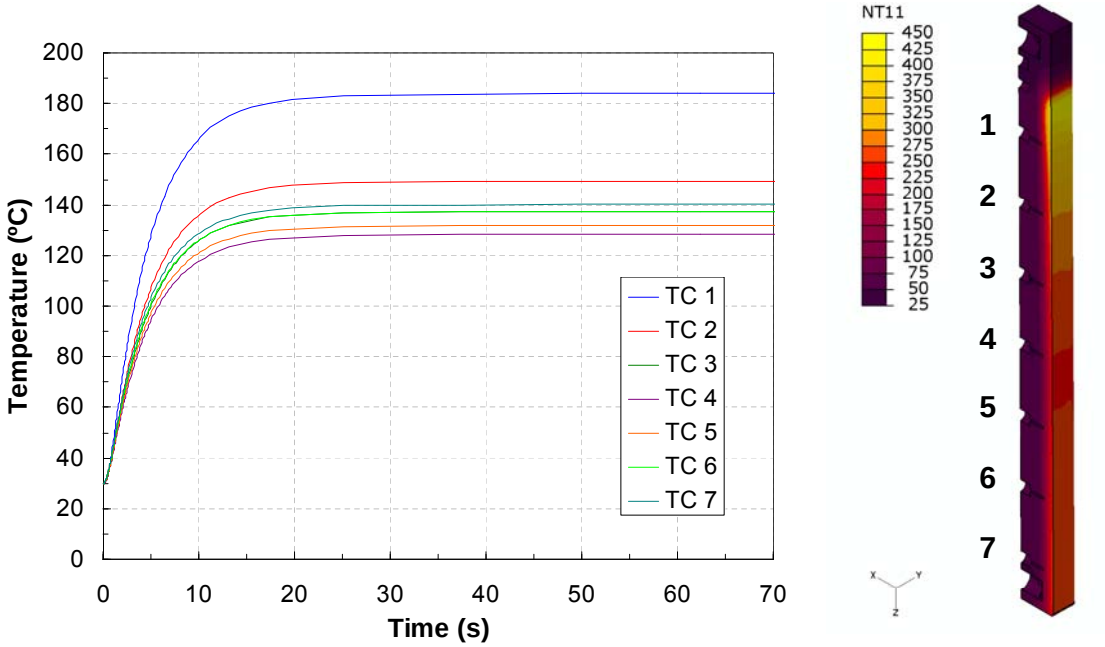
Mold Distortion Conclusions

- Mold distortion has a *significant* effect on taper
- The thermal distortion of each of the mold pieces, the effect of the changing funnel geometry, and the interfacial sliding of the wide and narrow faces all contribute to the effective taper seen by the solidifying shell, each in a *nonlinear* fashion with distance down the mold
- The thermal expansion of the wide face works against the applied taper and the effect of the funnel, so calculations based only on room-temperature dimensions are *insufficient*

Transient Behavior – Model Study

- Transient heat transfer analysis with ABAQUS
- Start from uniform 30 ºC
- Allow time stepping until steady state
  - Defined as maximum $\Delta T < 0.001$ ºC
  - Accuracy-controlled time step for max $\Delta T < 0.2$ ºC
- Steady state (by this definition) reached in 70 s
  - 37.2 hours wall clock on 8×2.66 GHz computer
    (excessive paging despite 8 GB RAM, might have memory bug)

Thermocouple Temperatures

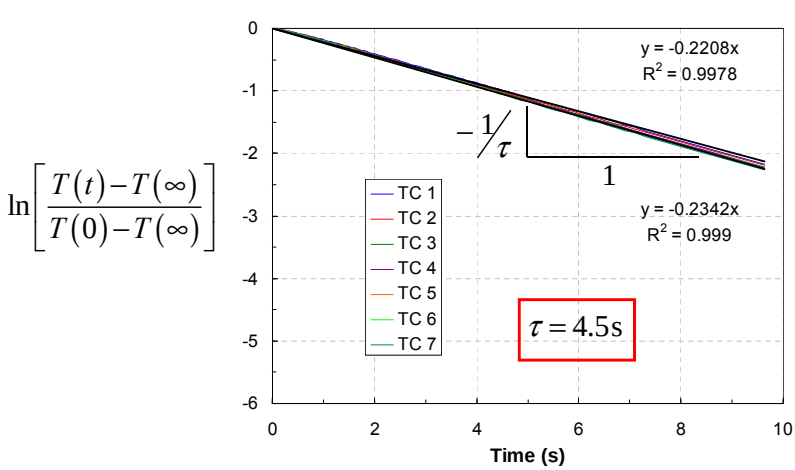


First-Order Response

- Many thermal systems exhibit first-order behavior

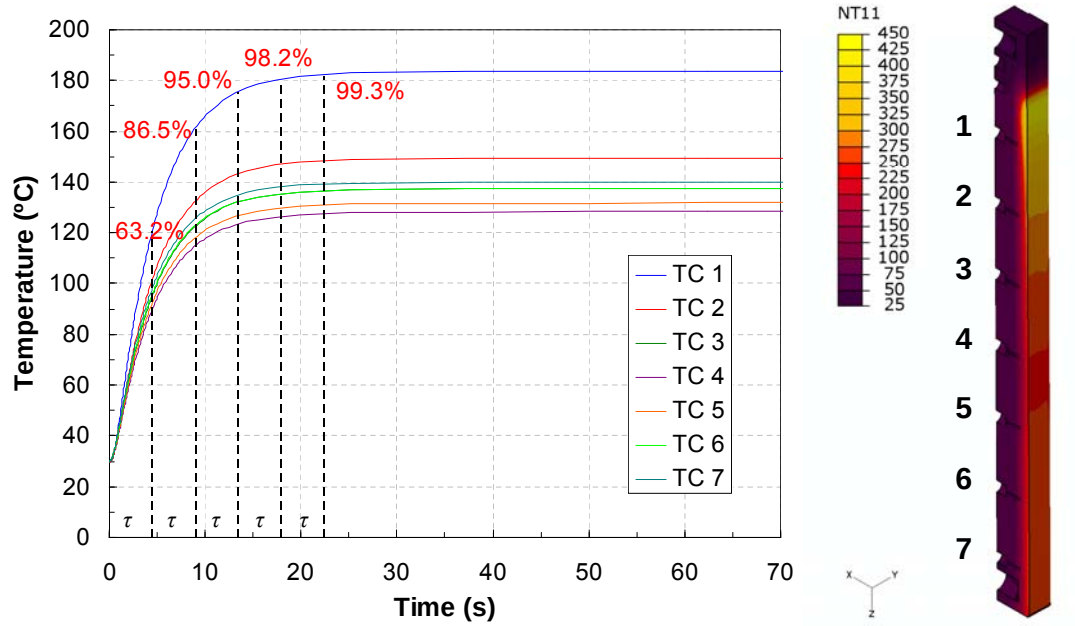
$$\frac{T(t)-T(\infty)}{T(0)-T(\infty)} = \exp\left(-\frac{t}{\tau}\right)$$

τ	Time Constant
$T(0)$	Initial Temperature
$T(\infty)$	Steady-state Temperature



First-Order Response

- Time constant characterizes transient behavior



Scaling Analysis

- The characteristic time for diffusion is

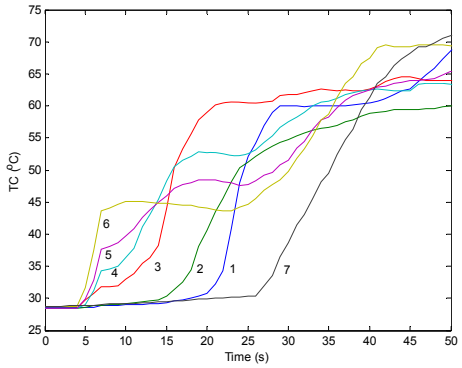
$$t_c = \frac{L^2}{\alpha}$$

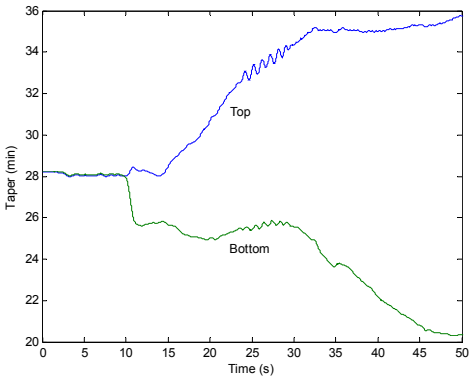
where L is a characteristic length and $\alpha = k/\rho \cdot c_p$ is the thermal diffusivity

- Using properties on slide 3 and L = 22.5 mm (average distance from hot face to channels), $\boldsymbol{t_c}$ **= 5 s** is the characteristic time
- "Back of envelope" agrees with FE model

Startup Transient

- Measured transient periods of about 15 seconds agree with prediction of time constant
- Measured top and bottom NF taper also show 15 second transient periods





Transient Behavior - Conclusions

- Time constant of NF mold calculated to be about 5 s
  - Transient periods take about 15 s
  - Measurements suggest this is approximately correct
- Measured slopes of mold exhibit same transients
  - Thermal behavior dictates mechanical behavior
- Higher frequency behavior likely stick-slip action at WF/NF interface

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