Thermal-mechanical model of solidifying steel shell behavior and its applications

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Outline

- Thermal-mechanical model of solidifying steel shell behavior: CON2D
  - Heat transfer and solidification model
  - Heat transfer boundary conditions (heat flux and resistors)
  - Stress model
  - Constitutive models for solid, mushy and liquid regions
  - Hot tear crack criterion
  - Validation

- CON2D applications
  - Thermal mechanical behavior of the shell ignoring the strand corner effect: Slice domain
    - Critical shell thickness due to membrane stress caused by ferrostatic pressure
  - Shell behavior with strand corner: 2-D L-shape domain
    - Maximum casting speed due to sub-mold bulging
  - Ideal mold taper prediction
Continuous casting process

* Courtesy of Hashio [Hashio et. al., Continuous Casting of Steel, Vol. 2, 1981]
Modeling challenges

- Inseparable, highly-nonlinear creep-plasticity constitutive behavior at high temperature
- Solid and liquid phases with moving interface
- Ferrostatic pressure from internal liquid
- Failure criterion to predict cracks
- Phase transformations (Solidification & Solid Phase transformation)
- And others
  - Coupled thermal and stress analysis
  - Contact between the shell and mold
  - Inherent 3D nature of the process
  - Parametric studies (increased computation)
Current model description

- Stepwisely coupled finite element thermal stress model.
- 2-D generalized plane strain to give 3D stress/strain state:
  \[ \dot{\varepsilon}^{\text{total}} = \dot{\varepsilon}^{\text{elastic}} + \dot{\varepsilon}^{\text{thermal}} + \dot{\varepsilon}^{\text{inelastic}} + \dot{\varepsilon}^{\text{flow}} \]
- Phase fractions from non-equilibrium Fe-C phase diagram for plain carbon steel and linear phase fraction model between liquidus and solidus for ferritic and austenitic stainless steels.
- Unified elastic-visco-plastic constitutive model.
- Treat liquid same as solid with nearly zero yield strength.
- Robust alternating implicit-explicit time integration scheme.
- Temperature dependent thermal and mechanical properties.
- Efficient contact algorithm between mold and shell surface.
Thermal mechanical model – CON2D

BCs: \( T(t), h(t), q(t) \)

Shell heat transfer model
\([k(T), H(T)]\)

\( T(t, x, y), f_{s, \alpha, \delta}(t) \)

Shell stress model
\([E(T), TLE(T), \varepsilon^{in}(T, \sigma, f_s, f_{\alpha}, f_{\delta}, t)]\)

\( u(t, x, y), \sigma(t, x, y), \varepsilon(t, x, y) \)

Mold
\([Taper(t), Distortion(t)]\)

Contact

[Hot tear criterion]

[Hot tear cracks(t,x,y)]
Phase fraction calculation

Heat resistor model across the mode wall and the interfacial layer between the mold wall and the steel surface couples the heat transfer and stress simulation.
Constitutive model for solid steel

- Mizukami [Mizukami, 1977] elastic modulus data changing with temperature
- Kozlowski constitutional equations for austenite [Kozlowski, 1991], and modified model for delta-ferrite [Parkman, 2000]:
  - Kozlowski model for austenite
    
    \[
    \dot{\varepsilon}(1/\text{sec.}) = f(\%C)\left[\sigma(MPa) - f_1(T(\circ K))\varepsilon\right]^{[\xi(T(\circ K))]} \exp\left(-4.465 \times 10^3 (\circ K)/T(\circ K)\right)
    \]
    
    \[
    \begin{align*}
    f_1(T(\circ K)) &= 130.5 - 5.128 \times 10^{-3} T(\circ K) \\
    f_2(T(\circ K)) &= -0.6289 + 1.114 \times 10^{-3} T(\circ K) \\
    f_3(T(\circ K)) &= 8.132 - 1.54 \times 10^{-3} T(\circ K) \\
    f(\%C) &= 4.655 \times 10^4 + 7.14 \times 10^4 \%C + 1.2 \times 10^5 (\%C)^2
    \end{align*}
    \]

  - Modified power law model for δ-ferrite
    
    \[
    \dot{\varepsilon}(1/\text{sec.}) = 0.1 \left[\sigma(MPa)\right]^{\left[f(\%C)\left(T(\circ K)/300\right)^{-5.52}(1+1000\varepsilon)^m\right]^n}
    \]
    
    \[
    \begin{align*}
    f(\%C) &= 1.3678 \times 10^4 (\%C)^{-5.56 \times 10^{-2}} \\
    m &= -9.4156 \times 10^{-3} T(\circ K) + 0.3495 \\
    n &= 1/1.617 \times 10^{-4} T(\circ K) - 0.06166
    \end{align*}
    \]
Liquid material treatment

- Highly strain rate dependent creep function to simulate perfect plastic behavior in the liquid with nearly zero yielding stress

\[
\dot{\varepsilon}^p = \begin{cases} 
10^8 \left( |\bar{\sigma}| - \sigma_{\text{yield}} \right)^5 & |\bar{\sigma}| > \sigma_{\text{yield}} \\
0 & |\bar{\sigma}| \leq \sigma_{\text{yield}} 
\end{cases}
\]

\[\sigma_{\text{yield}} = 0.01 \text{MPa}\]

- Other properties such as elastic modulus and thermal linear expansion are based on measured or extrapolated data.
Validation (B&W)

- Mesh: 0.1mm ~ 2.0mm
- $\Delta t = 0.001$ sec. ~ 0.1 sec.
Fully coupled simulation vs. plant practice*

Sulfur print of billet

CON2D results

* Park et. al. Ironmaking and Steelmaking, v29, 2002
Hot tear criterion in CON2D

Crack Criterion: Fracture occurs when $\varepsilon^D > \varepsilon^{Dc}$

Damage Strain, $\varepsilon^D$

$$\varepsilon^D = \sum_{90\%\text{ Solid}}^{99\%\text{ Solid}} (\varepsilon^{\text{flow}})$$

Damage threshold, $\varepsilon^{Dc**}$

$$\varepsilon_{ij}^{Dc} = \frac{0.02821}{\dot{\varepsilon}_{ij}(s^{-1})^{0.3131} \Delta T_B(^\circ C)^{0.8638}}$$

where:

$$\Delta T_B = T(f_s = 0.9) - T(f_s = 0.99)$$

for 0.27% C steel $\Delta T_B = 9^\circ C$

** This is the empirical equation by Y.M. WON et. al. based on many published measurements. [Met. Trans. B, Vol. 31B, August, 2000]
Thermal mechanical behavior of the shell ignoring the strand corner effect: **Slice domain**
Minimum shell thickness to avoid breakouts due to ferrostatic pressure

Diagram showing: Shell surface, Solidifying shell and mushy zone, Liquid steel, Solidifying Shell, Force Applied to Shell, Slab Thickness, W, Half Slab Width, Shell Thickness, b, Domain to be Molded, Ferrostatic Pressure, P.
Heat flux profiles

High speed

Local gap

Fitted Average Heat Flux Curve:
\[ Q = 4.05 \times t^{-0.33} \quad R=0.95 \]

Corresponding Instantaneous Heat Flux:
\[ Q = 12.40 \quad t < 0.01 \text{ sec.} \]
\[ 2.71 \times t^{-0.33} \quad t > 0.01 \text{ sec.} \]

Contact Time (sec.)

Casting speed: 1.0 m/min

Total Heat Extracted by Mold (MJ/m²)

- 65.5
- 37.0
- 13.4
- 7.4
Profiles through shell at mold exit
(Thicker and colder shell)

Ferrostatic pressure applied

2.2 m/min with good contact
(65.5 MJ/m²)

\[
Average\ stress = \frac{\rho g (b - 2t) H}{2t}
\]
Profiles through shell at mold exit
(Thinner and hotter shell)

Ferrostatic pressure applied

High speed or thick local gap
(7.4 MJ/m²)

Average stress = \( \frac{\rho g(b - 2t)H}{2t} \)
Effect of casting speed and section size on total strain

- 0.044% C carbon steel
- 1 °C superheat
- measured when plastic strain rate drops to 0.001 s⁻¹
Critical shell thickness

- Critical shell thickness as a function of carbon content (%C) for different energies (Q).
- Graph showing the relationship between critical shell thickness (mm) and working mold length (mm) for various conditions.

- Carbon Content (%C) vs. Critical Shell Thickness (mm) for different energies (Q).
- Strand Thickness (mm) vs. Critical Shell Thickness (mm) for different energies (Q).
- Working Mold Length (mm) vs. Critical Shell Thickness (mm) for different energies (Q).

- Energy (Q) values include 6.61 MJ/m², 4.66 MJ/m², 6.03 MJ/m², and 4.38 MJ/m².

- Carbon content ranges from 0.003 to 0.44.

- Strand thickness ranges from 50 to 400 mm.

- Working mold length ranges from 300 to 1100 mm.

- Graph includes data points for different materials and conditions, such as oil, slag, and different companies.

- Key materials and conditions include:
  - Mitsubishi
  - Solid
  - Q=6.61 MJ/m²
  - Q=6.34 MJ/m²
  - Q=6.03 MJ/m²
  - Q=4.66 MJ/m²
  - Q=6.03 MJ/m²
  - Q=6.34 MJ/m²
  - Q=6.56 MJ/m²
  - Q=6.89 MJ/m²
  - Q=4.38 MJ/m²
  - Q=5.78 MJ/m²
  - Q=6.34 MJ/m²
  - Q=6.56 MJ/m²
  - Q=6.89 MJ/m²

- Graphs illustrate the critical shell thickness for different conditions and materials, with various heat treatments and energy levels.
Shell behavior with strand corner: 2-D L-shape domain
Maximum casting speed to avoid excessive bulging

- Liquid Steel
- Solidified Shell
- Gap
- Tapered Distorted Mold
- Super Heated Liquid Steel
- L Shape Domain (CON2D)
- Ferrostatic Pressure

Casting Direction

Graph and image showing the casting process with annotations.
Heat flux profiles

- Lorento [B]
- Lorento fitted Eqn: 700mm Mold [A]
- J.K. Park: 0.1C%, 120mm * 120mm [C]
- Wolf fitted Eqn for slag casting [D]
- Wolf fitted Eqn for oil casting [D]
- C. Li fitted Eqn for Slab casting [E]
- Brimacombe fitted Eqn [F]
- C. Li fitted Eqn for Billet Casting [G]
- Thin Slab [C]
- Kapaj [I]

Dwell Time (sec)

Distance below meniscus (mm)

1.0 m/min
- 2.2 m/min
- 5.0 m/min
- 6.0 m/min
Deformed stress* and temperature contours

V = 2.2 m/min at 200mm below mold exit

V = 5.0 m/min at 200mm below mold exit

* Stress components perpendicular to the dendrite arms are shown here.
Deformed total strain* and temperature contours

- Strain (%)
- Temperature (°C)

V = 2.2 m/min at 200mm below mold exit

V = 5.0 m/min at 200mm below mold exit

* Strain components perpendicular to the dendrite arms are shown here.
Damage strain contours

- Strain (%)  
- Temperature (°C)

V = 2.2 m/min at the end of simulation (23 sec., 200mm below meniscus)

V = 5.0 m/min at the end of simulation (23 sec., 1000mm below meniscus)
Critical casting speeds vs. plant practice*

Ideal Taper Prediction: Slice and L-shape domains
Heat flux and surface temperature profiles

**Graphs:**

1. **Instantaneous Heat Flux (MW/m²):**
   - C Li fitted heat flux for Billet $6.5^*(t+1)^{-0.5}$
   - Various data points for different faces.

2. **Surface Temperature (°C):**
   - Two lines for 2.2 m/min and 4.4 m/min.
   - Distance Below Meniscus (mm) vs. Temperature.

**Legend:**
- H8117 Inner Face
- H8117 Left Face
- H8117 Outer Face
- H8117 Right Face
- H6334 Inner Face
- H6334 Left Face
- H6334 Outer Face
- H6334 Right Face

**Units:**
- Time Below Meniscus (sec.)
- Distance Below Meniscus (mm)
- Instantaneous Heat Flux (MW/m²)
- Surface Temperature (°C)
Mold distortion profile and heat transfer coefficient of spray zone
Longitudinal off-corner crack
- Stress* and damage strain contours (0.75% linear taper mold)

V = 4.4 m/min at 100mm below mold exit

* Stress components perpendicular to the dendrite arms are shown here.
Transverse cracks
- Stress (z) contours for the ideal taper mold (no gap)

V = 4.4 m/min at 100mm below mold exit

V = 4.4 m/min at 200mm below meniscus
Corner gap needed to generate uniform surface temp.

![Graph showing heat flux and gap size against distance to corner.](image-url)
Shrinkage predicted by slice model

![Graph showing shrinkage predicted by slice model](image)

0.27%C, 120 x 120 mm Section size

- 1.0 m/min
- 1.5 m/min
- 2.0 m/min
- 3.0 m/min
- 4.0 m/min
Summary - Applications

- **Thermal mechanical behavior of the shell ignoring the strand corner effect: Slice domain**
  - Predict the temperature, stress, and strain evolution through the solidifying shell ignoring the corner effect.
  - Good for all strand shapes (billet, slab, etc.).
  - Small computational cost.

- **Shell behavior with strand corner: 2-D L-shape domain**
  - Predict the temperature, stress, and strain evolution across a 2-D section of the strand.
  - Predict the distorted shape of the strand.
  - Good for billet and bloom and corner portion of the slab.
  - Substantial computational cost.

- **Hot tear cracks can be predicted by the hot tear criterion and damage strain calculated from the strain in the mushy region.**
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