CCC ANNUAL REPORT

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Modeling Steel Slab Heat Transfer During Scarfing Processing

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Objective and Methodology

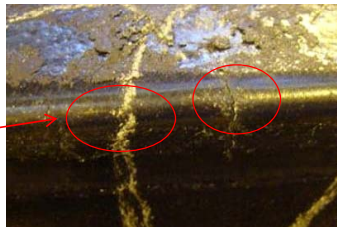
- Objective:
  - To get basic ideas of heat transfer mechanism in scarfing processing
- Methodology:
  - Experiment & Modeling to make prediction match measurements

Scarfing Processing

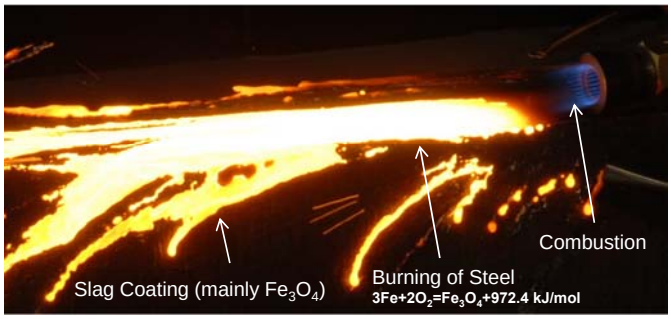
- Steel slab from continuous casting exhibits surface defects, including inclusions, pits and cracks
- Selectively-scarfing slab edges can remove corner cracks

1. Before Scarfing

Cracks



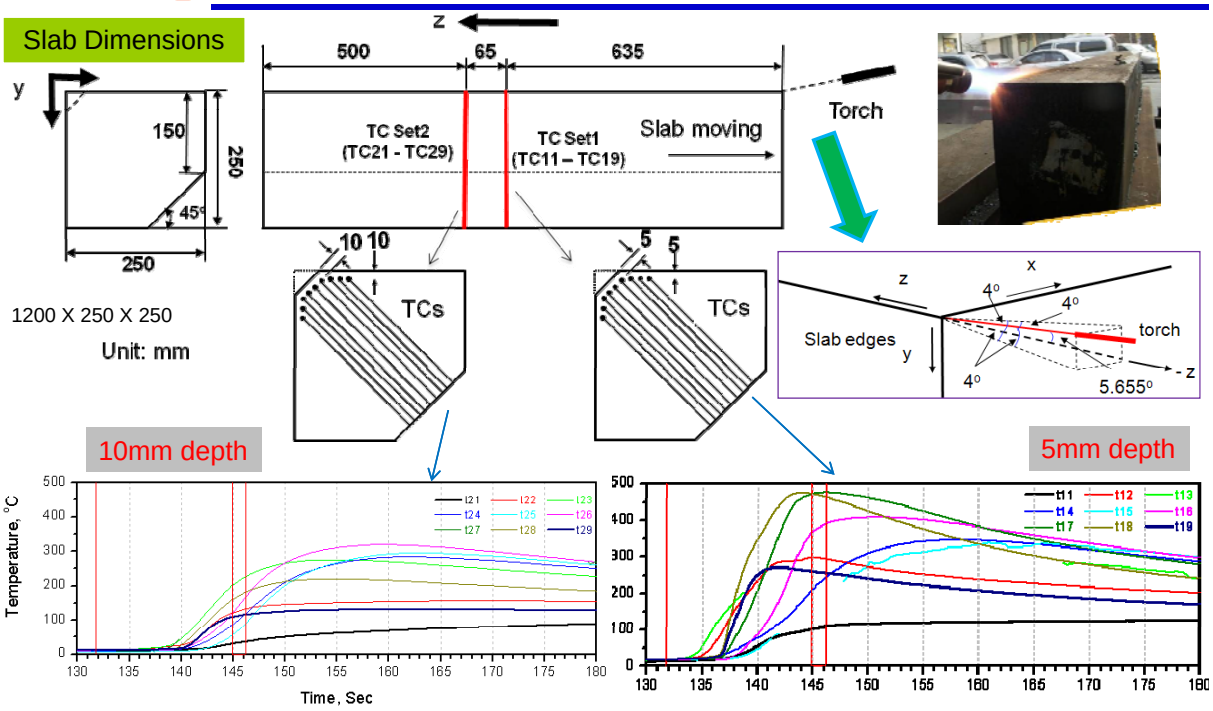
2. During Scarfing



3. After Scarfing

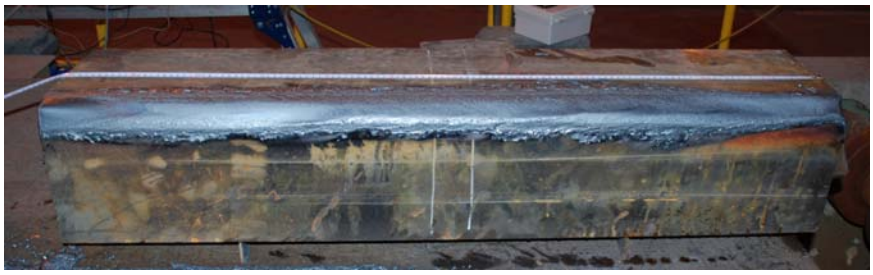
Scarfing Experiment

Slab Dimensions

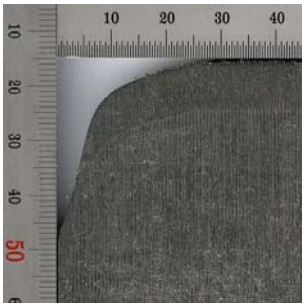


Pictures form Dr Kim's report "Design of In-line Edge Scarfing Nozzle Using Numerical Analysis"

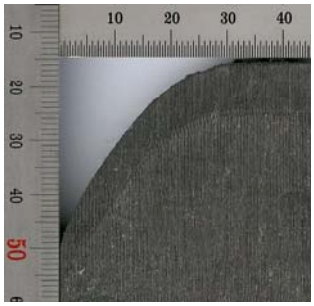
New Surface Profile
(Scarfing Surface)



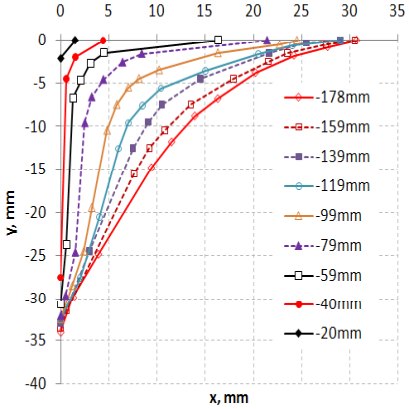
Typical Scarfed Cross-Section Profiles



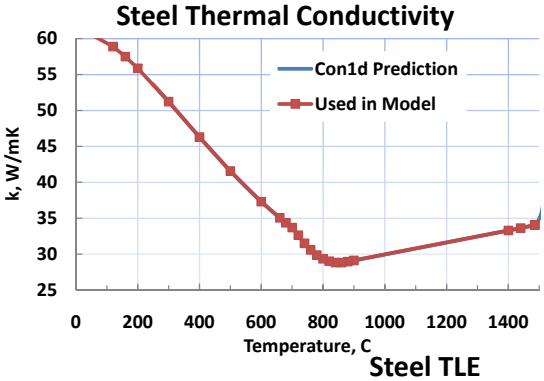
z = -99mm

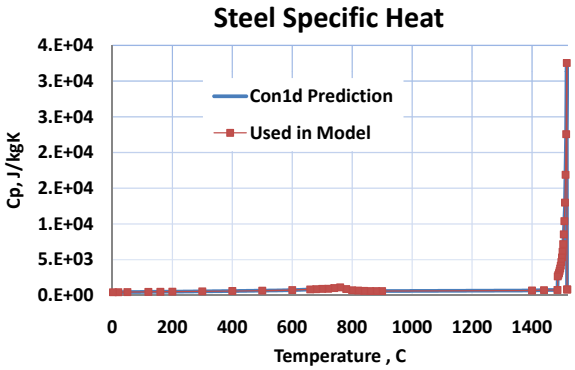


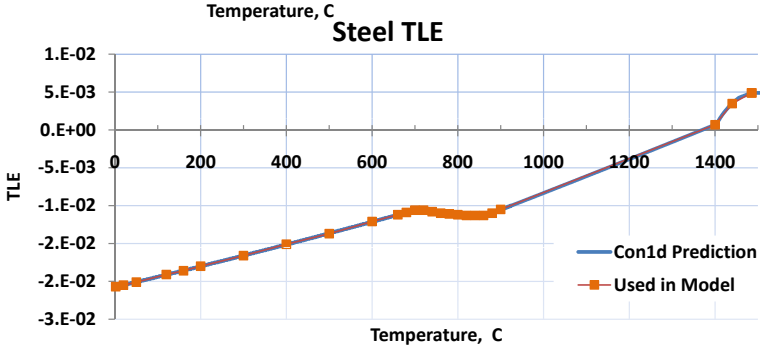
z = -178mm



Steel Thermal Properties
(CON1D Output)





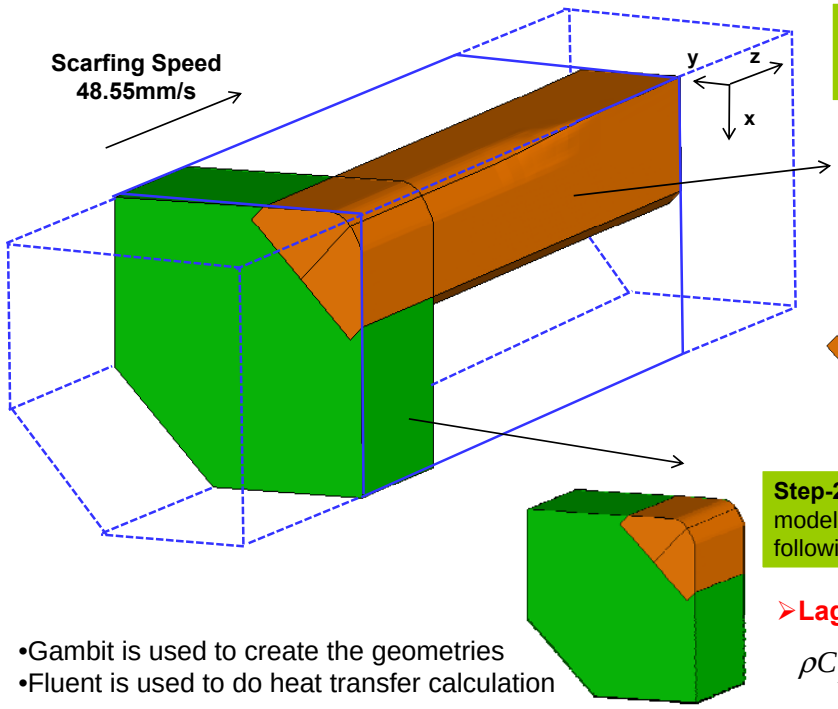


Steel Compositions by OES

C	0.07516	Al	0.03286
Si	0.22320	Cu	0.02754
Mn	1.25600	Nb	0.02590
P	0.01520	N	0.00330
S	0.00202		

Liquidus: 1516 °C
Solidus: 1486 °C

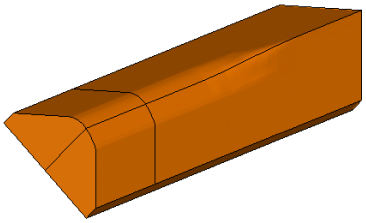
Two-Step Model



Step-1 model: Steady state heat transfer model with advection to get the first 12.3 s temp history

➢**Eulerian Method**

$$\rho C_p(T)\vec{V} \bullet \nabla T = \nabla \bullet (k(T)\nabla T)$$



Step-2 model : Transient heat transfer model without advection to get the following 110s temp history

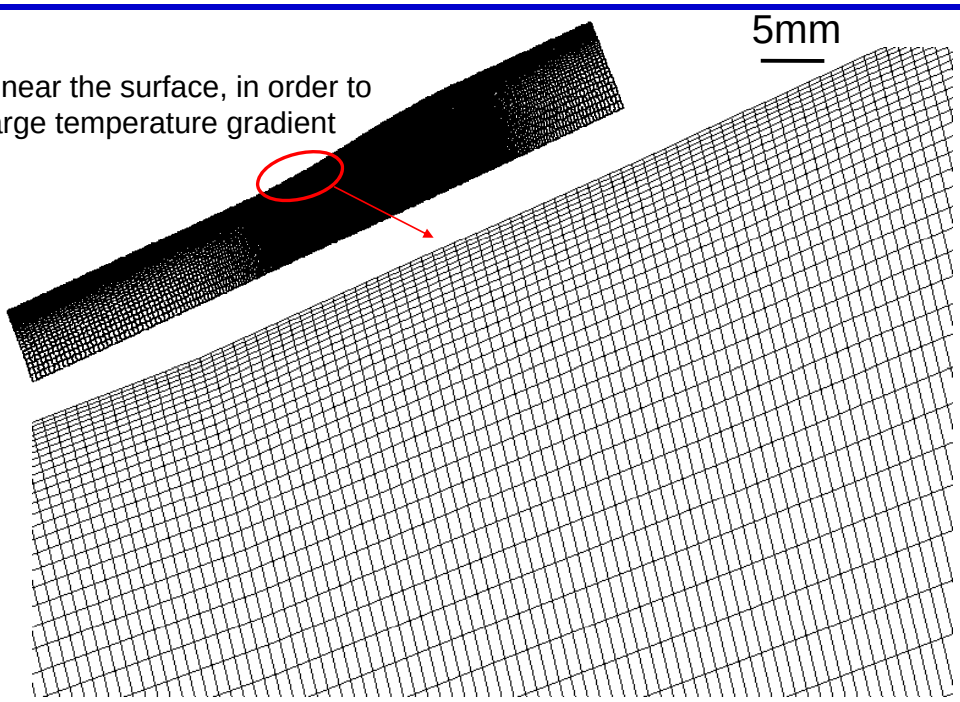
➢**Lagrangian Method**

$$\rho C_p(T)\frac{\partial T}{\partial t} = \nabla \bullet (k(T)\nabla T)$$

•Gambit is used to create the geometries
•Fluent is used to do heat transfer calculation

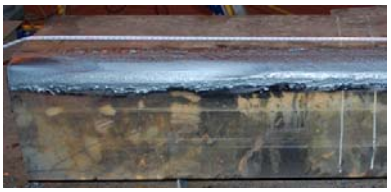
Step-1 Model Mesh over Diagonal Plane

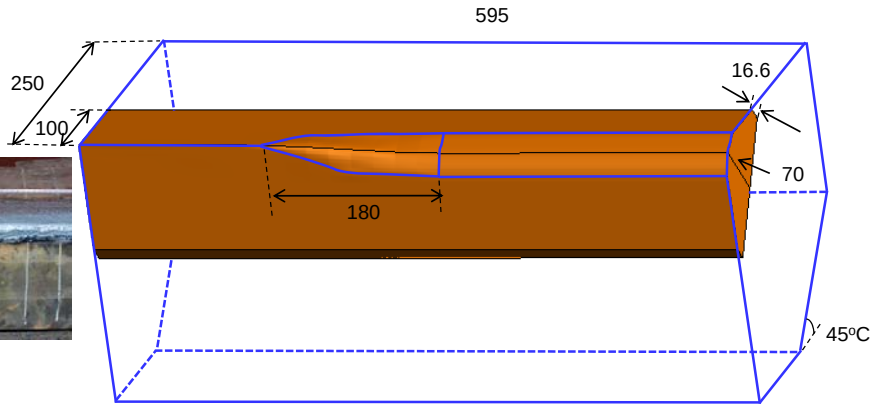
❑ Mesh is finer near the surface, in order to capture the large temperature gradient



Step-1 Model
Domain and Dimensions

Unit: mm





The solution to the **semi-infinite heat transfer problem** will be valid if the following criterion is satisfied[****]

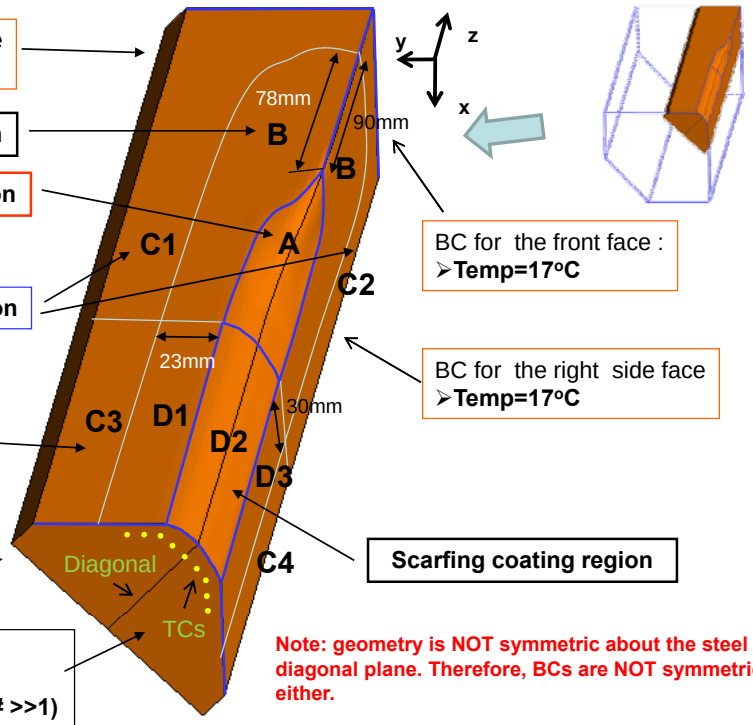
$$t < \frac{H^2}{16\alpha}$$

Here: $\alpha = \left.\frac{k}{\rho C_p}\right|_{steel} = \frac{30\frac{W}{mk}}{7400\frac{kg}{m^3}1000\frac{J}{kgK}} = 4\times10^{-6}\frac{m^2}{s}$ $\quad t = \frac{595mm}{48.55mm/s} = 12.3s$ =>H > **28** mm

Step-1 Model takes longer width and depth to guarantee this criterion.

[***]Refer to P94-97 in J. Danzig and C. Tucker's book *Modeling in Materials Processing*

Step-1 Model
Boundary Conditions



BC for the left side face
➢**Temp=17°C**

Slag coating region

Scarfing reaction region

Forced convection region

Convection region

BC for the bottom face:
➢**Temp=17°C**

BC for the back face :
➢**Heat flux=0**
(by scaling analysis, Peclet # >>1)

BC for the front face :
➢**Temp=17°C**

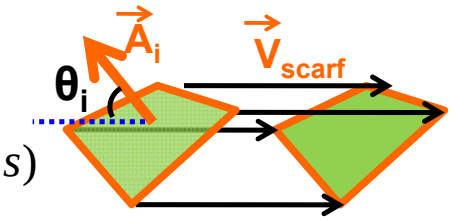
BC for the right side face
➢**Temp=17°C**

Scarfing coating region

Note: geometry is NOT symmetric about the steel slab diagonal plane. Therefore, BCs are NOT symmetric either.

Boundary Condition for Region A

➢**Region A—Scarfing Reaction to specify BC**



1. Volumetric rate of removal of iron:

$$\dot{V}_{ox,i}(m^3/s) = A_i(m^2)\cos\theta_i V_{scarfing}(m/s)$$

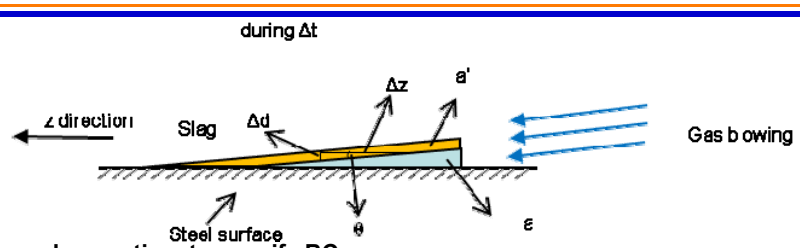
2. Local heat flux:

$$q''_{A,i}\left(\frac{W}{m^2}\right) = \gamma_{scarfing}\frac{\dot{V}_{ox,i}(m^3/s)\rho_{Fe}(kg/m^3)\Delta H_{scarfing}(J/kg)}{A_i(m^2)}$$

Constants:

- $\triangle H_{scarfing}$=5.803 X 10^6 J/kg
- ρ_{Fe} =7100kg/m^3
- $\gamma_{scarfing}$ a tuning parameter accounting for the fraction of heat that conducted directly into the steel slab in region A from scarfing reaction; calibrated to be 10.3%
- A_i is element area
- θ_i is angle between scarfing direction and element face normal

Boundary Condition for Region B



- **Region B—Continuous slag coating to specify BC**
  - Rate of increase in slag thickness:

    $\dot{\zeta}_{slag\_B}$ = *Δd/Δt = V_{scarf} tan(θ) ~0.048 m/s * tan(3º)*

  - Average local rate of mass deposition onto an element of surface B:

    $$\dot{m}_{slag\_B,i}(kg/s) = \zeta_{dist\_B}\dot{\zeta}_{slag\_B}(m/s)A_i(m^2)\rho_{slag}(kg/m^3)$$

  - ζ_{dist_B} increases linearly from 0.2 along the boundary with region C, to 1 along the boundary with region A, accounting for the increase of the slag layer thickness over the length of region B.
  - Local Heat flux: $$q''_{B,i}\left(\frac{W}{m^2}\right) = \gamma_{slag\_B}\frac{Cp_{slag}(J/kgK)(T_A - T_0)(K)\dot{m}_{slag\_B,i}(kg/s)}{(A_i)(m^2)}$$
  - γ_{slag_B} is a tuning parameter accounting for the fraction of heat conducted from the hot slag into the steel slab and is found to be 5.43%
  - T_A is the temperature of the slag generated in region A (assumed to be 4000 ºC, and T_0 is the reference temperature which is 0 K.

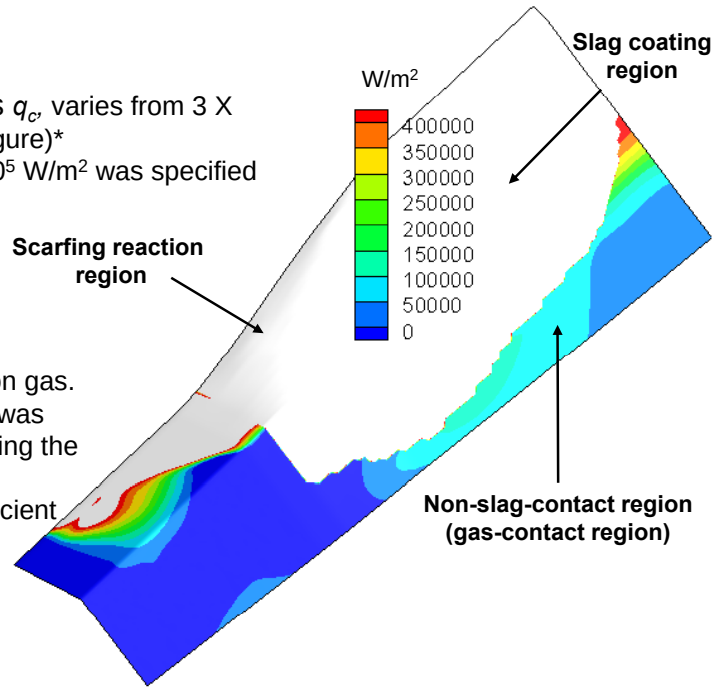
Boundary Condition for Region C

Region C1 and C2:

- Previous work by Dr. Kim shows q_c, varies from 3 X 10^4 W/m^2 to 4 X 10^5 W/m^2 (right figure)*
- An average heat flux q_C of 2 X 10^5 W/m^2 was specified in regions C1 and C2.

Region C3 and C4:

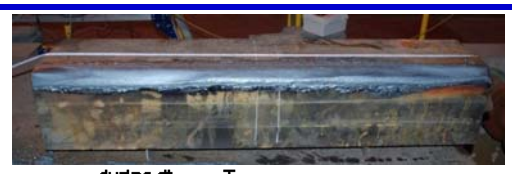
- Not heated by the hot combustion gas.
- The gas over region C3 and C4 was sucked into region C1 and C2 during the experiment.
- An estimated heat transfer coefficient (100 W/m^{2}K) is specified in region C3 and C4.

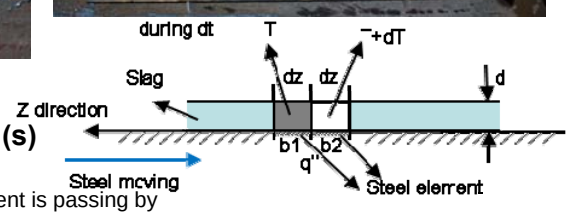


*Dr Kim's report "Design of In-line Edge Scarfing Nozzle Using Numerical Analysis"

Boundary Condition for Region D

❖As clearly seen, slag coating exists on the new scarfing surface and also on the surface generated by material removal.





1. Infinitesimal Steel element in dt goes from b1 to b2, and heat increment of dQ is conducted from the slag to this element:

dQ (J) = q''(z) (W/m^2) dz (m) dw (m) dt (s)

2. dQ can also be the heat decrease in the slag while steel element is passing by

dQ (J) = γ_{slag_D} ρ_{slag} (kg/m^3) Cp_{slag} (J/kgK) (T-(dT+T)) (K) (dz dw d) (m^3)

3. dz = V_{scarf} dt . Combine three equations together to get hear flux in Region D:

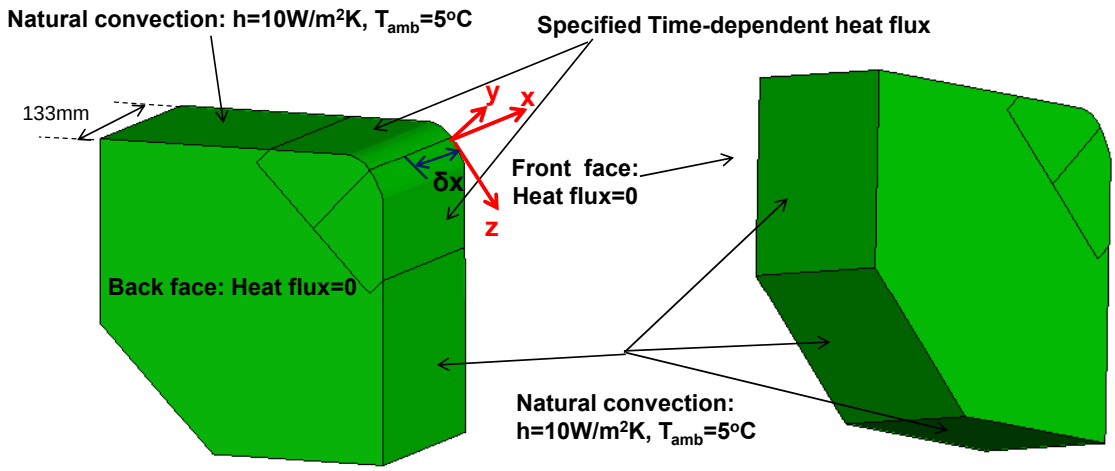
$$q''_{D\_i}(z_i)\left(\frac{W}{m^2}\right) = \gamma_{slag\_D}\rho_{slag}(kg/m^3)Cp_{slag}(J/kgK)\zeta_{dist\_D}\zeta_{slag\_D}(m)V_{scarf}\frac{dT}{dz_i}$$

Constants:

- γ_{slag_D} is calibrated to decrease from 36 % at region D entrance to 18% at region D exit.
- ζ_{slag_D} is the slag thickness of 5 mm; dT/dz_i is approximated as $(T_{B/D}-T_{D/Step-2})/\Delta z_D$
  - where $T_{B/D}$ is the temperature (1900 ^oC) of the slag as it enters region D (D1, D2 and D3)
  - $T_{D/Step-2}$ is the slag temperature (1100 ^oC) as it exits region D
  - Δz_D is the length of region D (266.4mm)

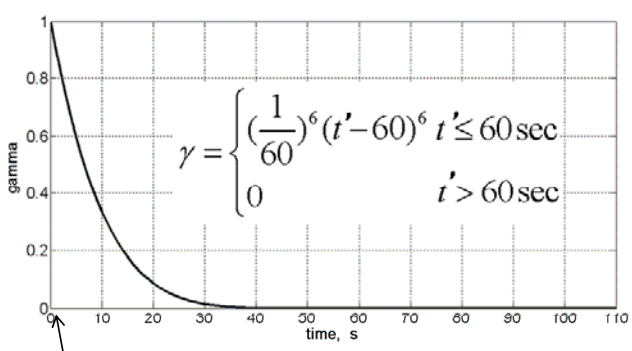
BACK2

Step 2 Model
Domain & Boundary Conditions



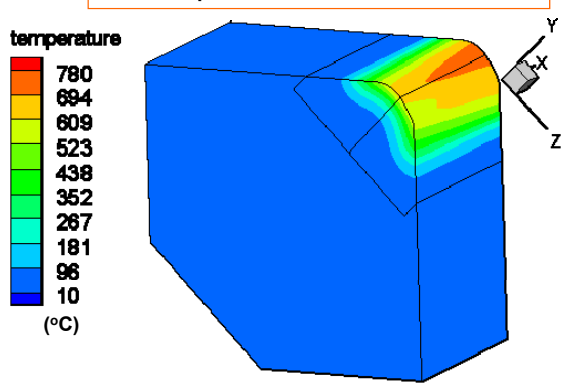
Step 2 Model
Top faces BC & Initial Condition

- **Region D—Slag coating heat transfer model to specify BC**
  - $q_{2\_slag,i} = q_{D,i}\ \gamma_{time}(t_i)$
  - $\gamma_{time}(t_i)$ is a tuning parameter to account for the time dependency of the heat flux (left bottom figure)
  - $t_i = t + \delta z/V_{scarf} - 9.14 = t' + \delta z/V_{scarf}$ (where $t' = t - 9.14$)



(9.14s global time)

Initial temperature distribution is taken from Step 1 Model from the same location.



Time Line of Events

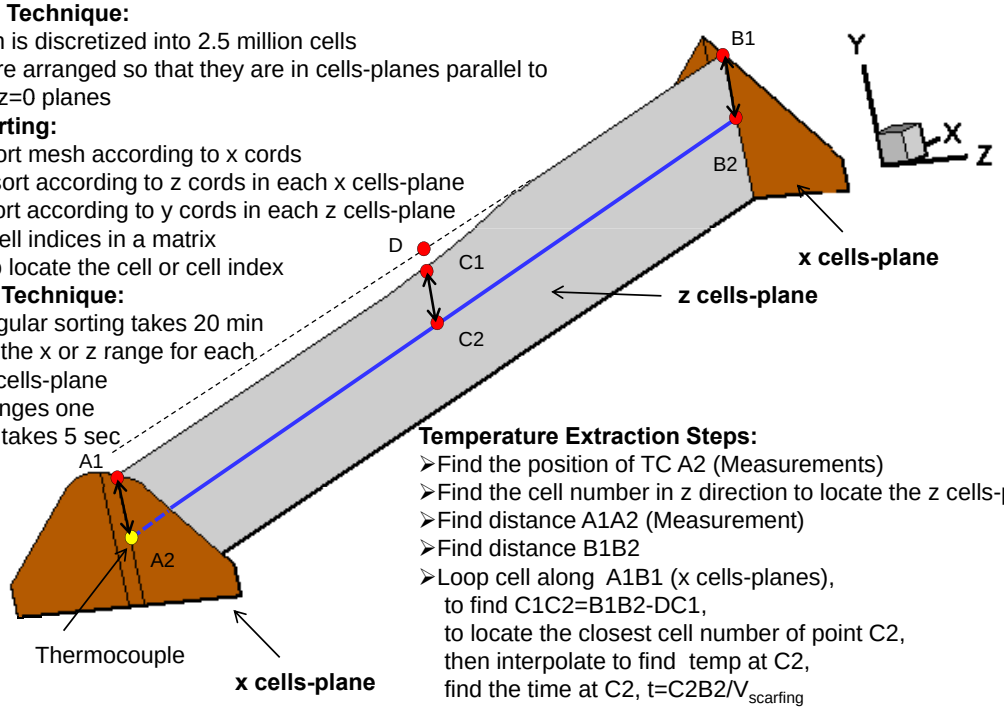
Time, s	Events
-50.00	Start of preheating
-9.37	End of preheating
-7.74	Torch end passes the slab corner
-3.06	Thermocouple TC set 1 enters Step-1 model domain (front face)
-1.72	TC set 2 enters Step-1 model domain
0.00	**TC set 1 passes B/A interface (at the diagonal line)**
1.34	TC set 2 passes B/A interface (at the diagonal line)
3.71	TC set 1 passes region A/D interface
5.36, 6.66	Torch end passes TC sets 1, 2
9.14	Step-2 model starts (TC set1 passes back face of Step-2 model domain and stays at back face of Step-2 model domain.)
119.14	Simulation ends

Data Extraction in Step 1 Model

Meshing Technique:
- Domain is discretized into 2.5 million cells
- Cells are arranged so that they are in cells-planes parallel to x=0 or z=0 planes

Cells Sorting:
- First, sort mesh according to x cords
- Then, sort according to z cords in each x cells-plane
- Last, sort according to y cords in each z cells-plane
- Store cell indices in a matrix
- Easy to locate the cell or cell index

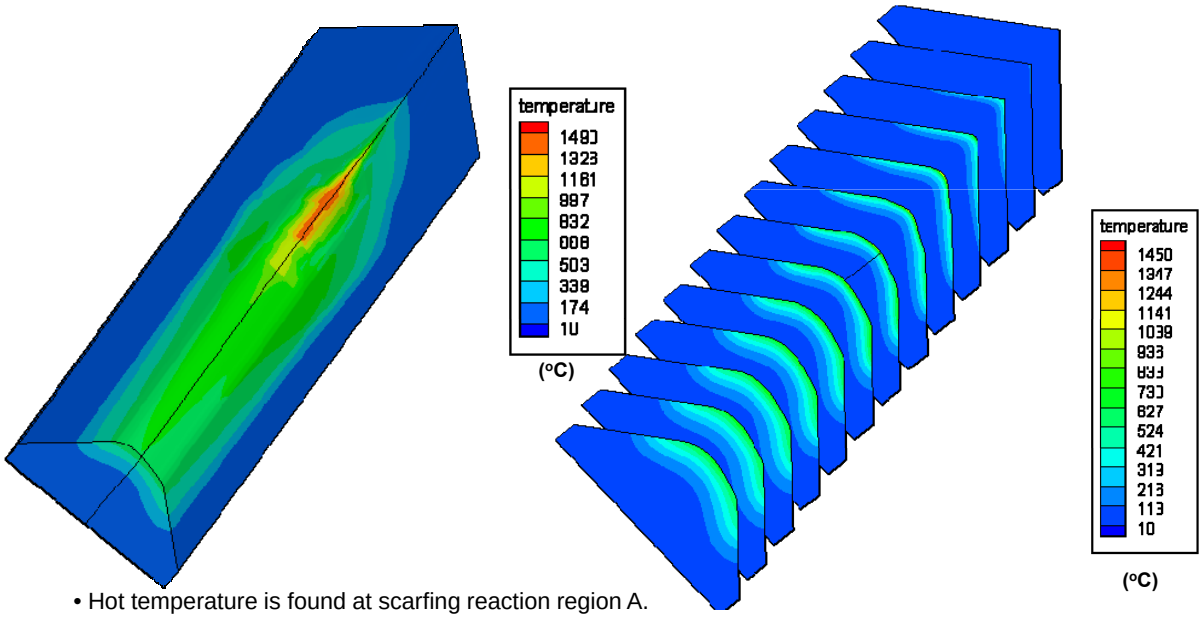
Another Technique:
- One regular sorting takes 20 min
- Output the x or z range for each x or z cells-plane
- With ranges one sorting takes 5 sec



Temperature Extraction Steps:
- Find the position of TC A2 (Measurements)
- Find the cell number in z direction to locate the z cells-plane
- Find distance A1A2 (Measurement)
- Find distance B1B2
- Loop cell along A1B1 (x cells-planes), to find C1C2=B1B2-DC1, to locate the closest cell number of point C2, then interpolate to find temp at C2, find the time at C2, $t=C2B2/V_{scarfing}$

Step 1 Model Results

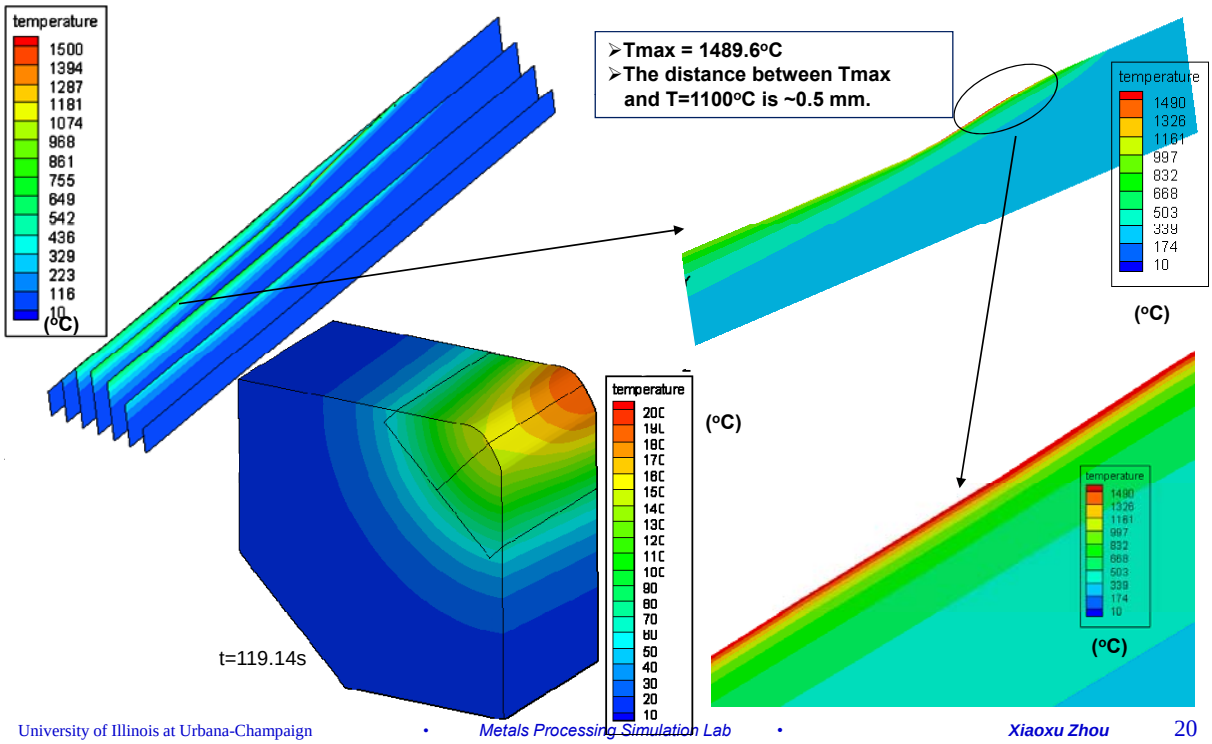
Temperature Distribution



- Hot temperature is found at scarfing reaction region A.
- Most heat is transported from upstream to downstream by simple advection of the moving slab.

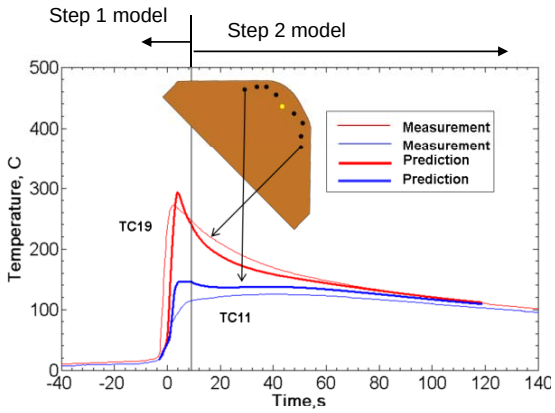
Step 1 Model and Step 2 Model Results

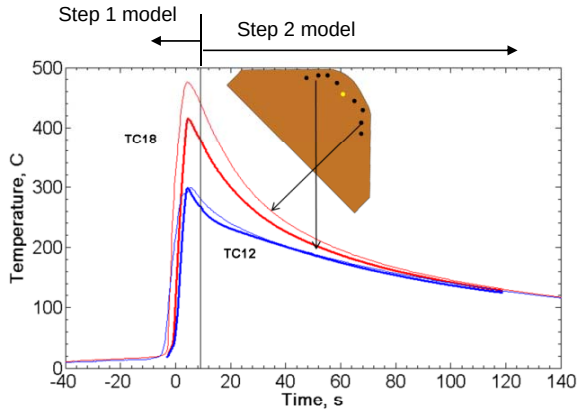
Temperature Distributions



TC Set1 (Shallow, 5mm in depth)

Prediction vs Measurement

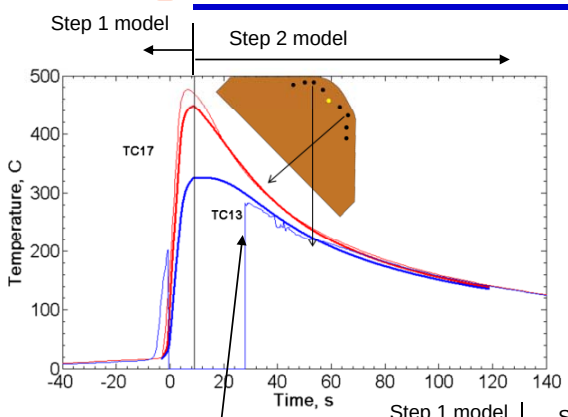


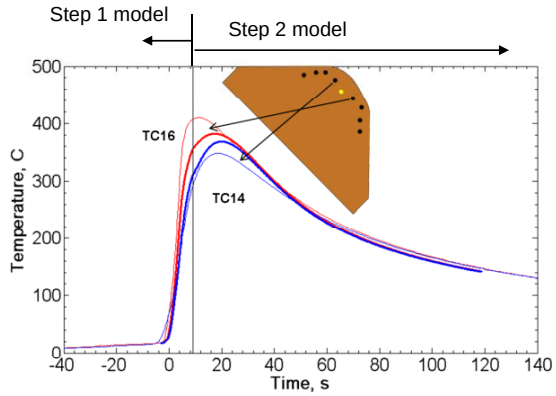


Measurement
Measurement
Prediction
Prediction

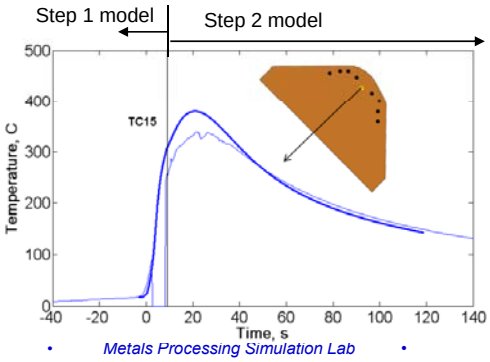
TC Set1 (Shallow, 5mm in depth)

Prediction vs Measurement





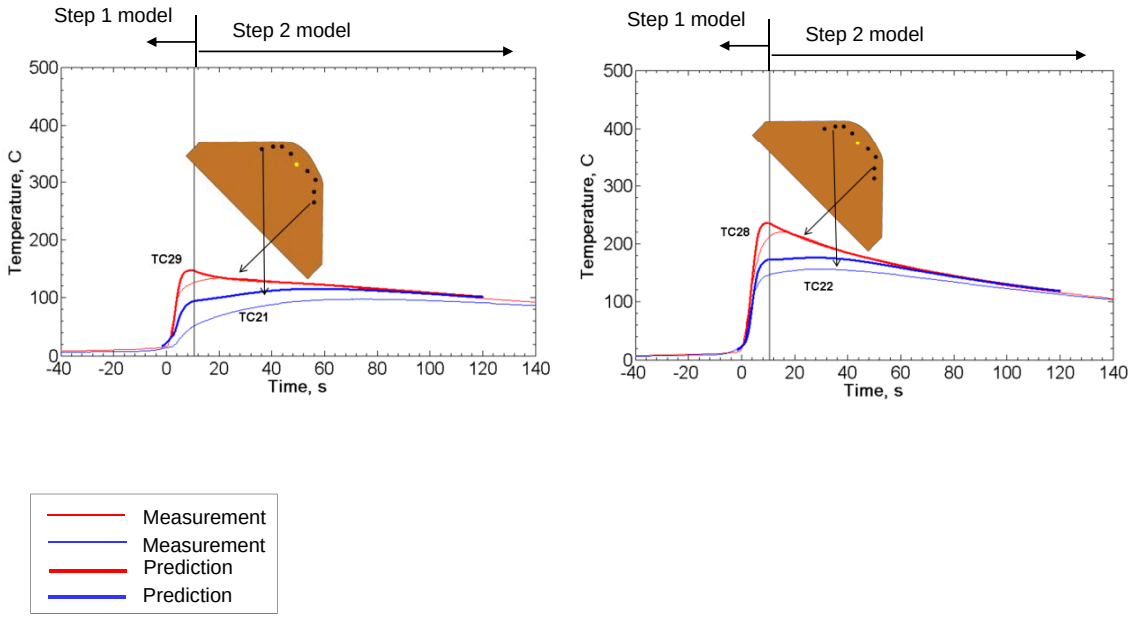
TC measurement missing



Measurement
Measurement
Prediction
Prediction

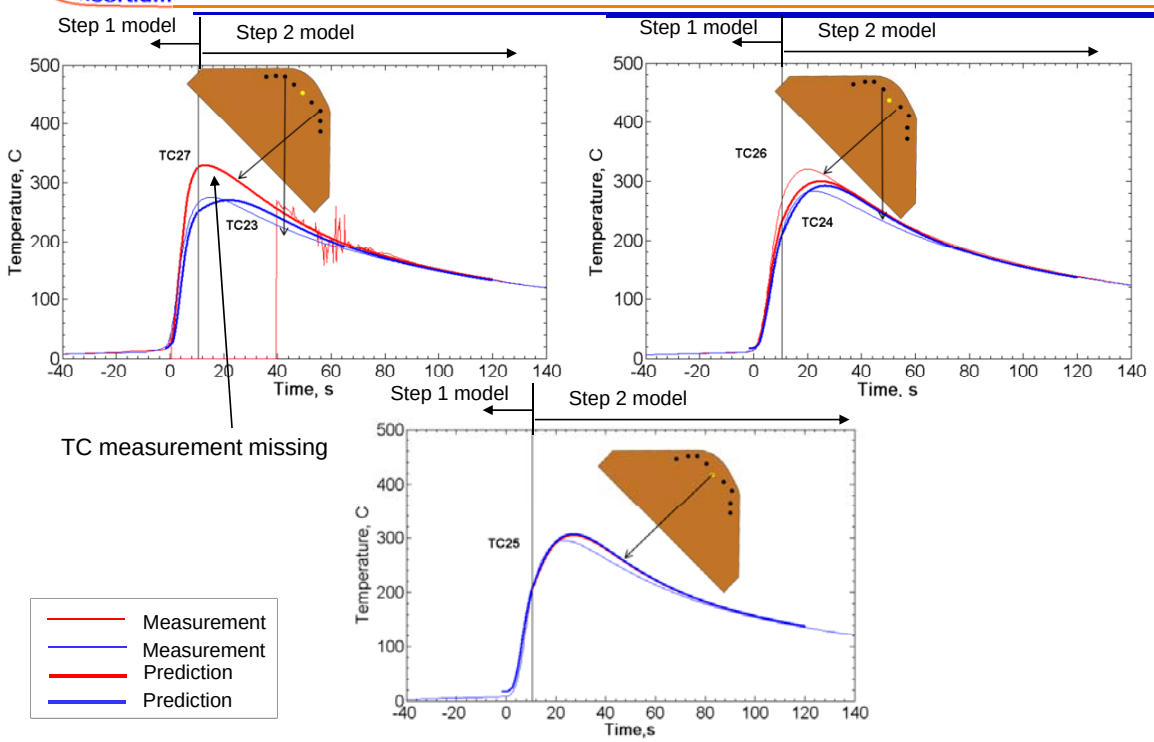
TC Set2 (Deep, 10mm in depth)

Prediction vs Measurement

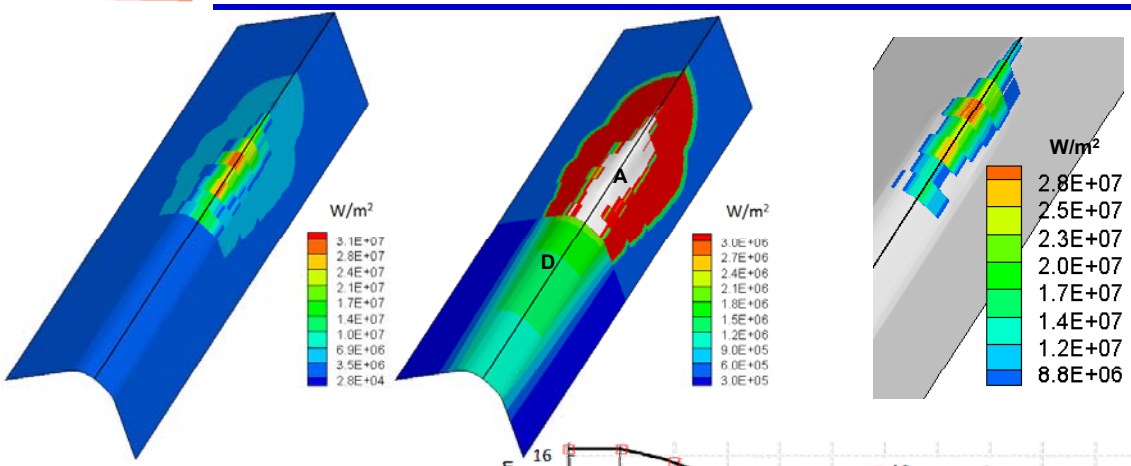


TC Set2 (Deep, 10mm in depth)

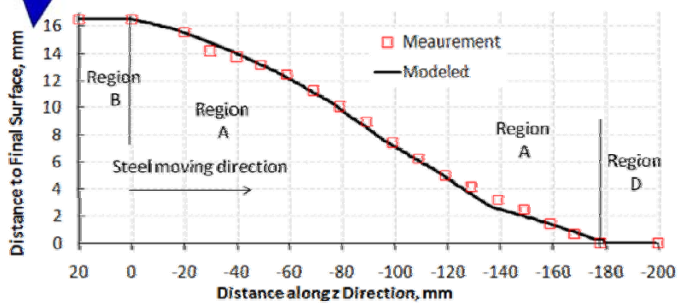
Prediction vs Measurement



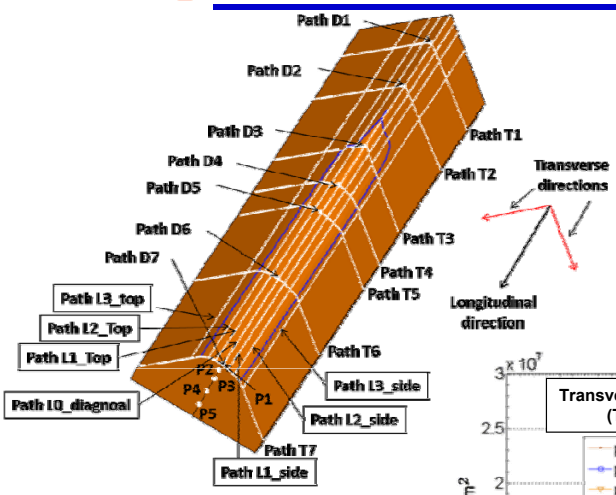
Surface Heat Flux Distribution
(Step 1 Model)

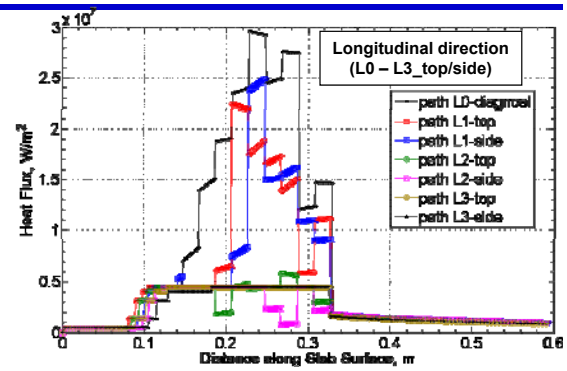


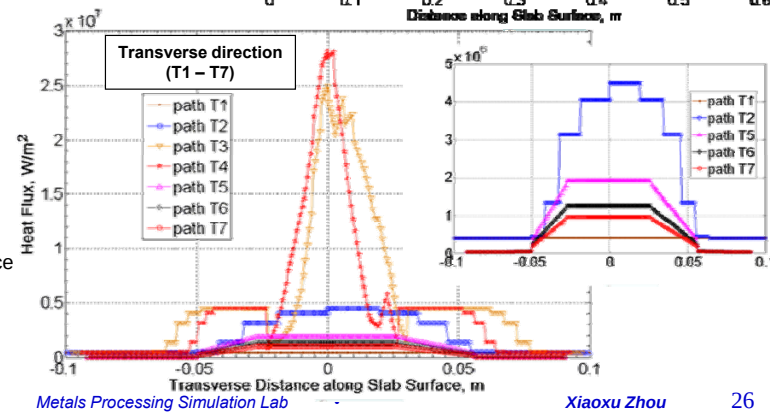
- The heat flux discontinuity between region A and region D is caused by the discontinuity of the measured surface slope, shown in the right.
- The sudden transition to a flat surface suddenly eliminates the scarfing reaction heat source



Surface Heat Flux Distribution along Longitudinal and Transverse Directions

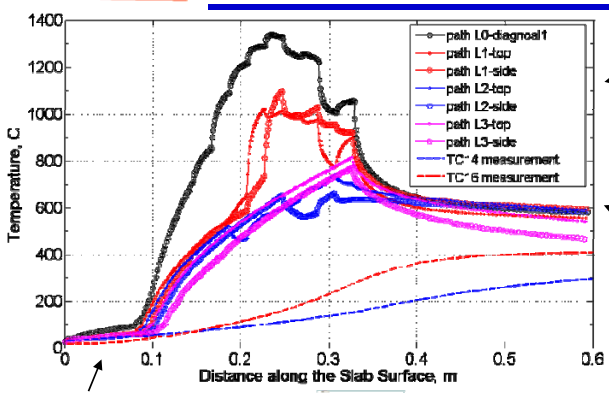






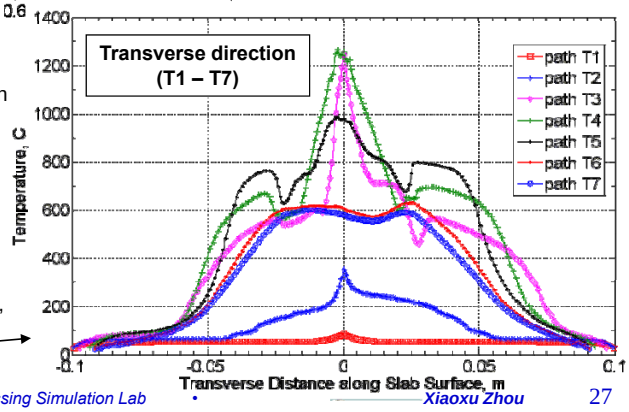
•Heat flux discontinuity with region A or B is caused by the discontinuity within curved surface (scarfed surface) or the discontinuity of the heat flux tuning parameter ζ_{dist_B}.

Surface Temperature Distribution along Longitudinal and Transverse Directions



Longitudinal direction (L0 – L3_top/side)

Note:
These paths follow the slab surface, so are not straight lines

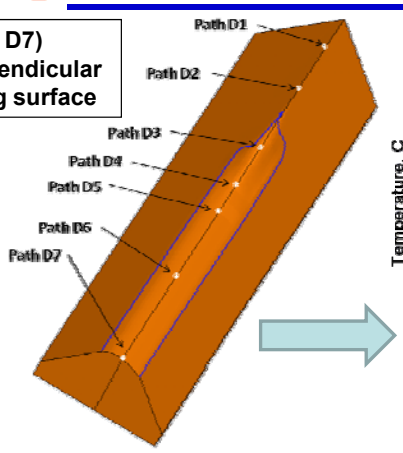


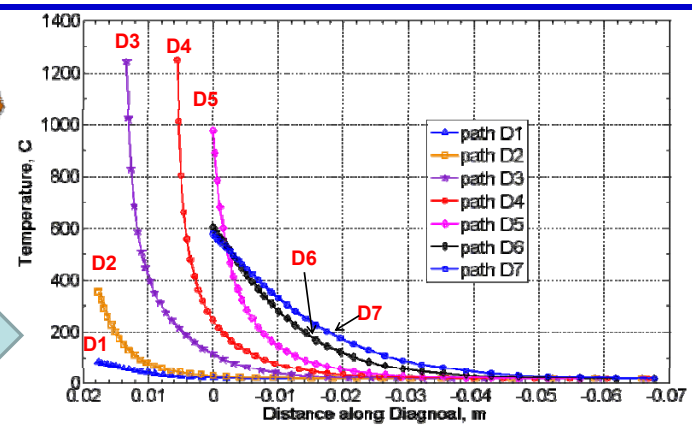
- Temperature of the slab surface goes up gradually from 17 °C to ~80 °C by combustion gas heating, then it goes up quickly in region B.
- After region B, steel enters region A for path 0, 1 and 2 or into region D for the off-diagonal path 3.
- Temperature wiggles along paths in region A are caused by the discontinuity of the surface heat flux.
- Finally, all temperatures decrease slowly in region D.

- The temperature profiles are not symmetric about the diagonal, which is due to the asymmetric shape that controls the heat generated by the scarfing reaction

Temperature Profiles beneath Surface at the Diagonal

(D1 – D7) Paths perpendicular to scarfing surface



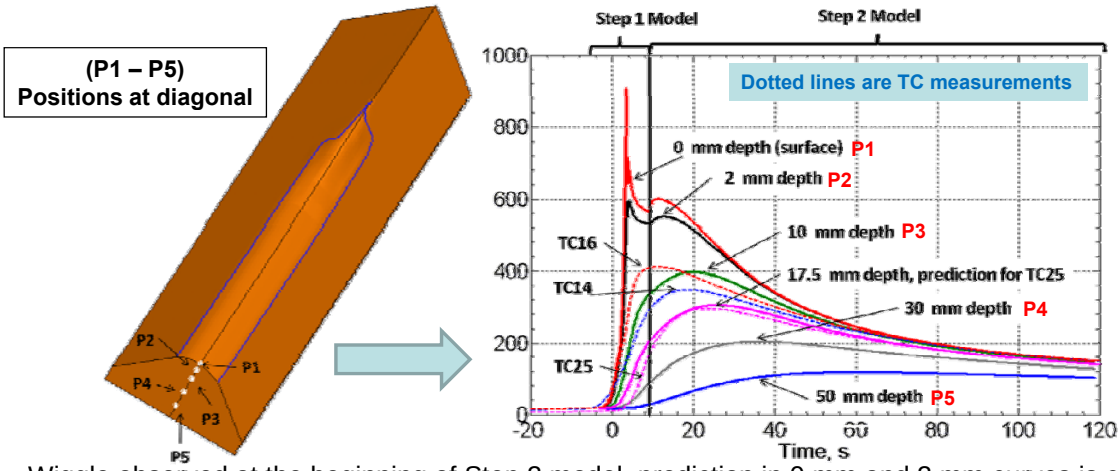


- Positive distances indicate location in the un-scarfed material (or remaining material) and negative distances indicate the depth into the final slab.

- Inner slab temperature increases gradually due to heat conduction penetrating from the hot region near the slab surface.

- The steel deeper than 50mm is not much affected, which again confirms the Step-1 model domain size assumption.

Temperature History Profiles for P1 – P5 at Diagonal



• Wiggle observed at the beginning of Step 2 model prediction in 0 mm and 2 mm curves is caused by the inconsistency of surface heat flux between region D and the Step-2 model.

• Heatup of TC25 (measurement) is further delayed by 1.34s, owing to its different z-position along the length of the slab.

• With increasing depth, there is an increasing delay before the TC "feels" the heat diffused from the scarfed region.

• The maximum temperature along the diagonal is ~900 ^{o}C . The maximum cooling rate is found on the surface on the order of 10 ^{o}C/s, martensite is unlikely unless steel is highly alloyed.

Summary and Future Work

- A novel two-step model is developed in Fluent and applied to simulate three-dimensional heat transfer during the scarfing processing.
  - The model includes detailed heat-transfer boundary models for the scarfing surface and the slag coating surfaces.
  - The two-step model combines an Eulerian model of steady heat transfer with a Lagrangian model of transient heat transfer get comprehensive temperature predictions of the entire process for 122.2 sec.
  - Such parameters are embedded: (1) $\gamma_{scarfing}$, (2) γ_{slag_B}, (3) γ_{slag_D}, (4) $\gamma_{time}(t_i)$ to make the temperature prediction match thermocouple measurements.

- Temperature predictions match TC measurements fairly well.
- The fraction of heat from scarfing reaction into steel slab is relatively small (10.3%).
- The fraction of heat from slag coating into the steel slab is relatively small (5.43%).
- Heat from the scarfing reaction and the consequent slag coating dominates the temperature evolution while the forced convection by high temperature flame and combustion gases does not affect heat transfer very much.
- With increasing depth, there is an increasing delay before the TC "feels" the heat diffused from the scarfed region.
- The maximum temperature along the diagonal is ~900 ^{o}C .The maximum cooling rate is found on the surface on the order of 10 ^{o}C/s, martensite is unlikely unless steel is highly alloyed.

- **Future work**: thermal stress analysis

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