Integrated model for the prediction of microstructure in the HAZ for X80 linepipe

The welding group

The Centre for Metallurgical Process Engineering

The University of British Columbia

EVRAZ NSERC CRSNG TransCanada

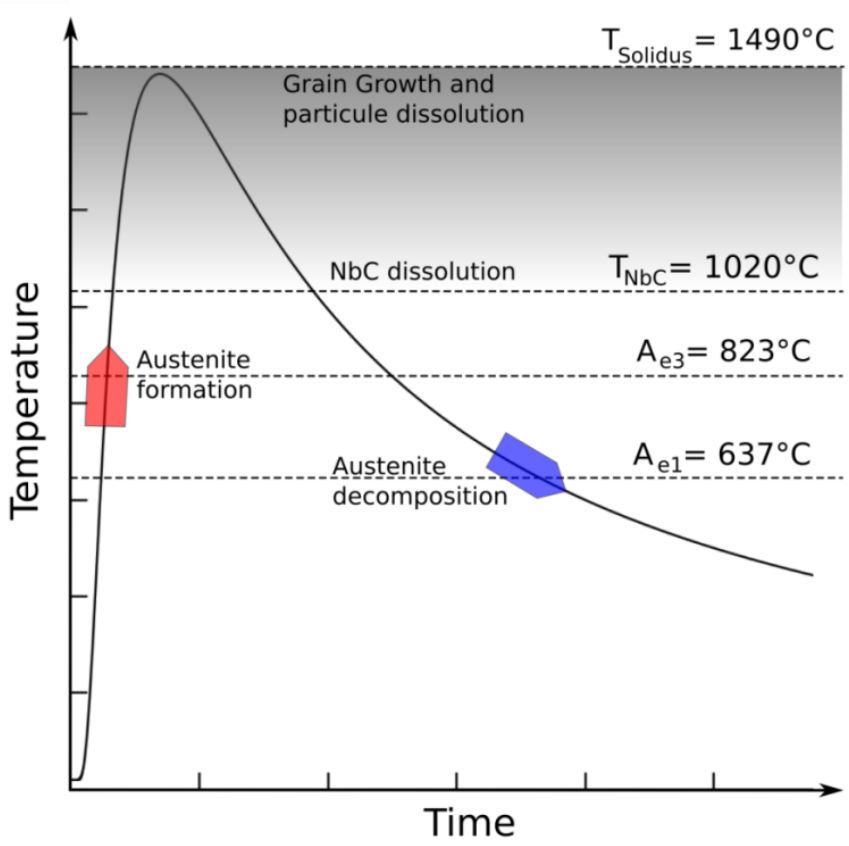
Modelling Approach

1) **Systematic studies** of austenite grain growth and austenite decomposition

2) **Construct sub-models** for each phenomena

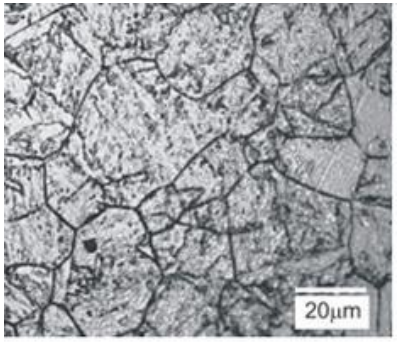
3) **Integrate sub-models** into single *fortran* program

4) **Validate predictive capabilities** for application to the HAZ

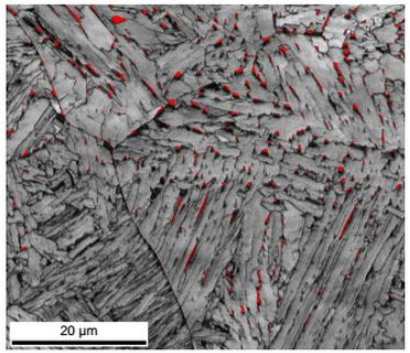


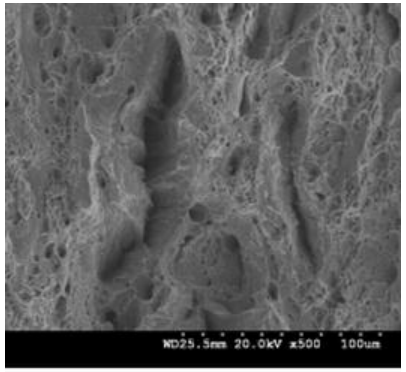
Metallurgical Phenomena

1) Austenite grain growth and precipitate dissolution



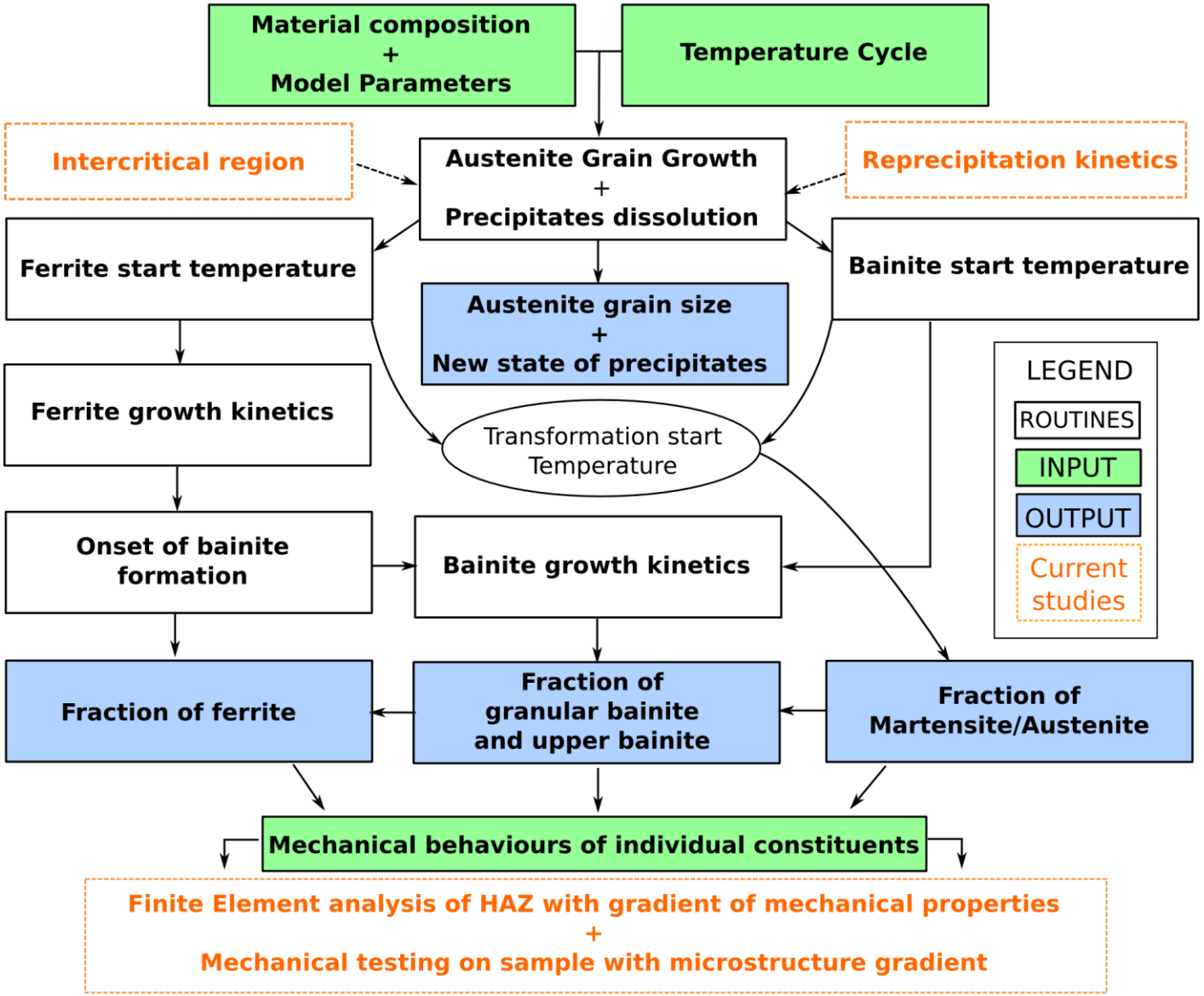
2) Austenite decomposition
   1) Transformation start temperature
   2) Ferrite and Bainite growth
   3) Martensite/Austenite fraction





3) Microstructure, mechanical properties relation

Integrated model



Dissolution of Precipitates and Grain Growth

Dissolution kinetics

$$\frac{dr_j}{dt} = \frac{D}{r_j} \frac{X - X_{Nb}^{j}(r_j)}{v_{at}^{M} X^{P} / v_{at}^{P} - X_{Nb}^{j}(r_j)}$$

Grain growth kinetics

$$\frac{dD}{dt} = M \left(\frac{\alpha\gamma}{D} - P_Z \right)$$

Interface curvature effect

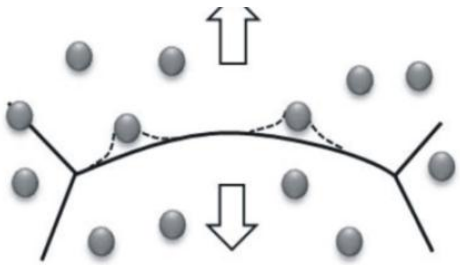
$$X_{Nb}^{j}(r_j) X_C = K_{NbC} \exp\left(\frac{4\sigma v_{at}^{P}}{r_j k_B T} \right)$$

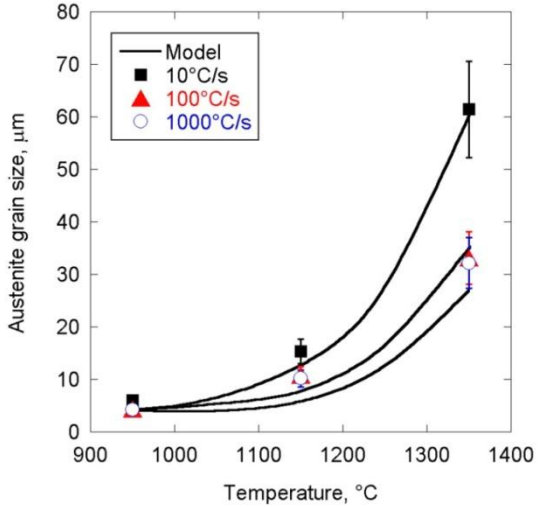
Grain boundary mobility

$$M = M_0 \exp(-Q / RT)$$

Pinning pressure

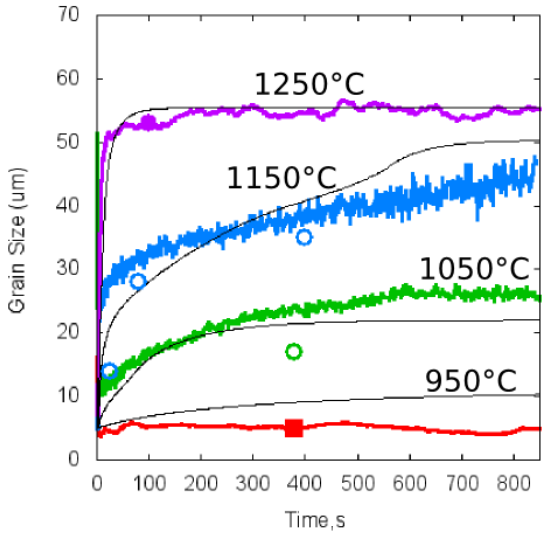
$$P_P = b \sum_{i}^{n} \frac{f_i}{r_i}$$

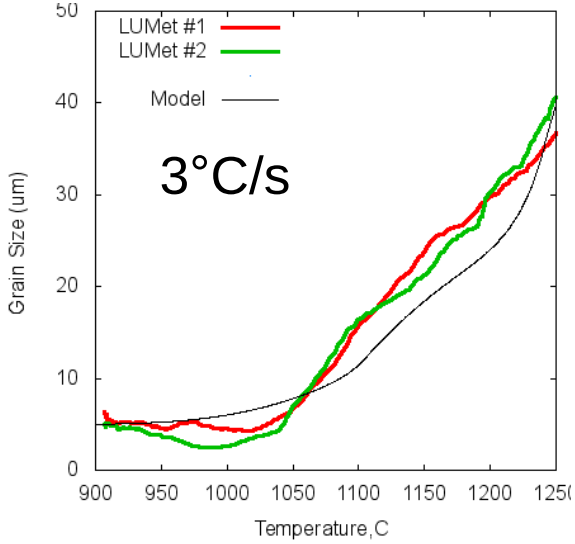


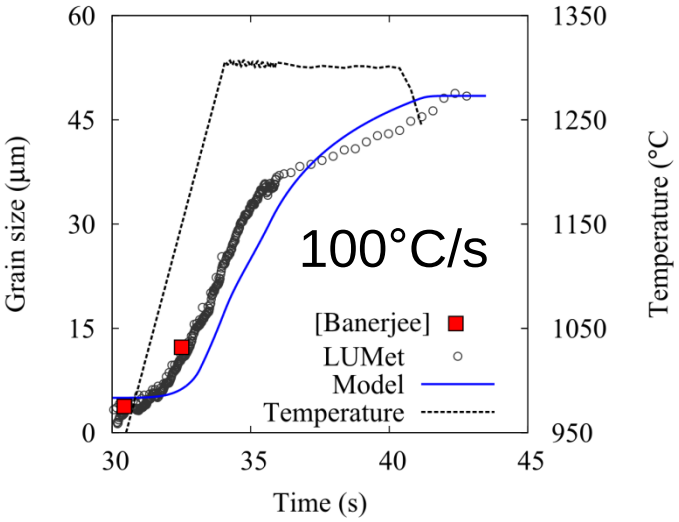


Austenite Grain Growth

- Isothermal grain growth tests (Limiting grain size)
- Continuous heating experiments (Heating rate)
- Conventional Metallography + Laser Ultrasonics







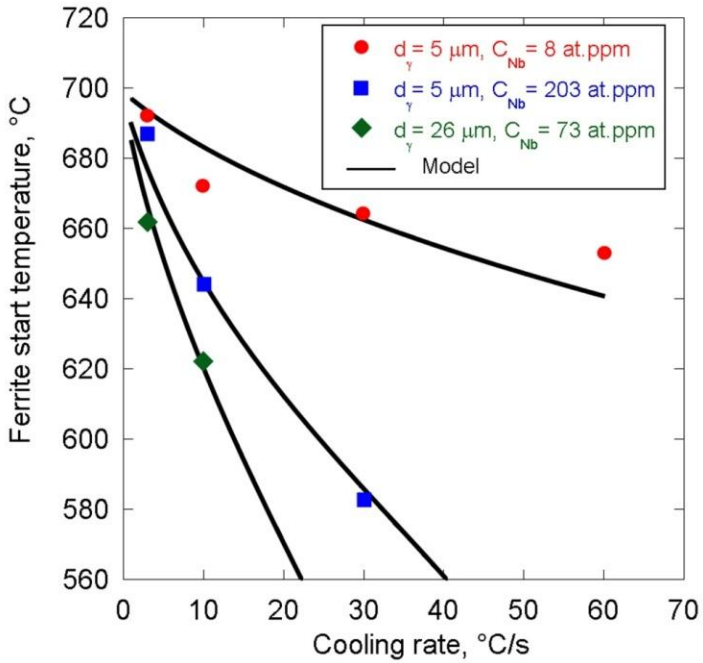
EVRAZ NSERC CRSNG TransCanada

Validation of Transformation Start Model

Ferrite start Model

$$\frac{dR_f}{dt} = D_C \frac{C^{\gamma} - C_o}{C^{\gamma} - C^{\alpha}} \frac{1}{R_f} \left(1 + \frac{D_C \alpha C_{Nb}}{R_f}\right)^{-1}$$

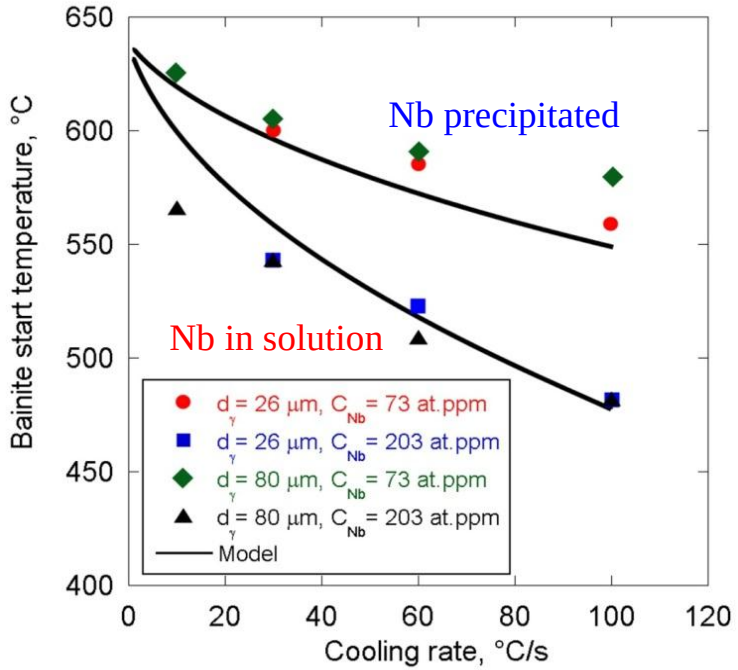
$$R_f > \frac{1}{\sqrt{2}} \frac{C^* - C_o}{C^{\gamma} - C_o} d_{\gamma}$$



Bainite start Model

$$0.05 = \int_{B_N}^{B_S} \frac{b_1 + b_2 T}{1 + b_3 C_{Nb}} \frac{dT}{\psi}$$

$$B_N = 640 - 143 X_{\alpha}^{1/2} + 288 X_{\alpha} - 528 X_{\alpha}^{2} + 646 X_{\alpha}^{3} - 380 X_{\alpha}^{4}$$

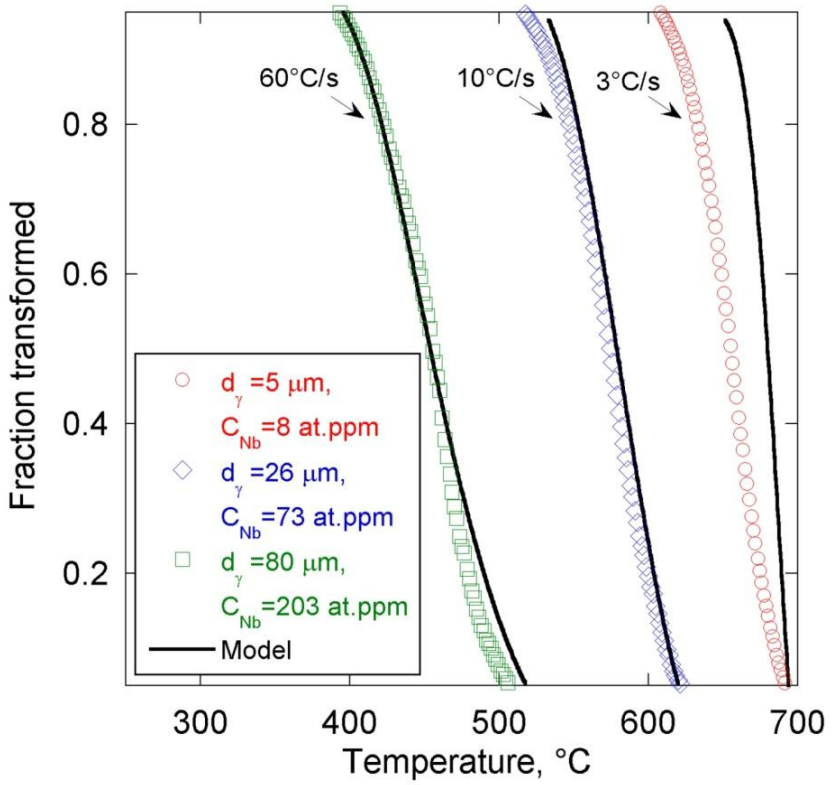


Ferrite and Bainite growth model

- Evaluation of a normalized fraction transformed X

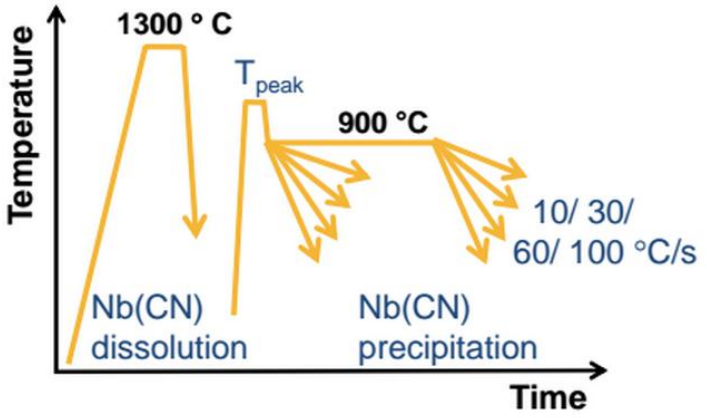
$$X = 1 - \exp\left(- \frac{1}{d_{\gamma}^{m}} \int_{T}^{T_S} \frac{\beta(T, c_{Nb})}{\psi(T)} dT \right)^{n}$$

- Ferrite fraction: $F=XF_{eq}$
- Bainite fraction: $B=X(1-F-M/A)$



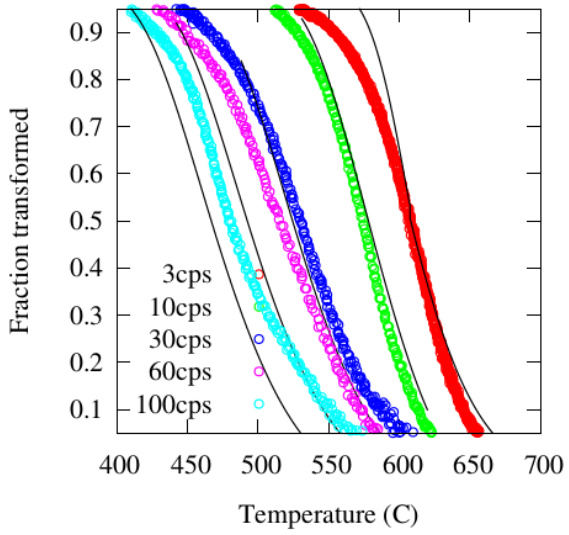
Austenite decomposition

- 2 levels of Nb considered in CCT tests
  - Nb fully in solution (0 min. at 900 °C)
  - Nb partially precipitated (20 min. at 900 °C)

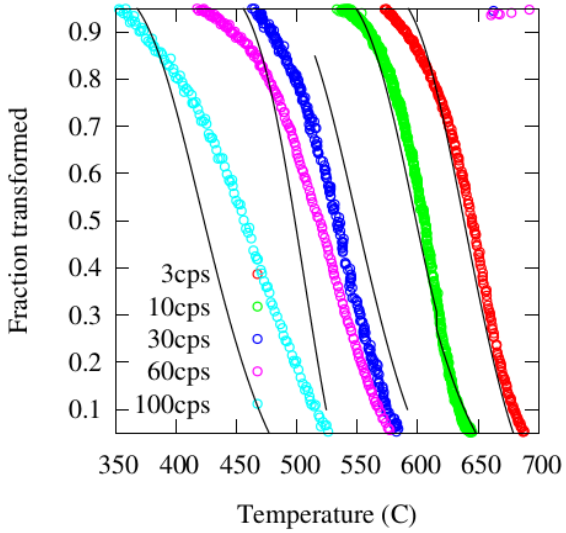


- 3 Prior austenite grain sizes

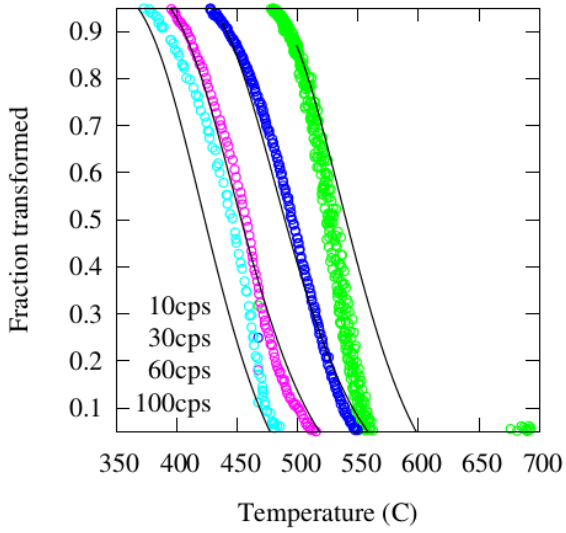
26µm Precipitated



5µm Solution



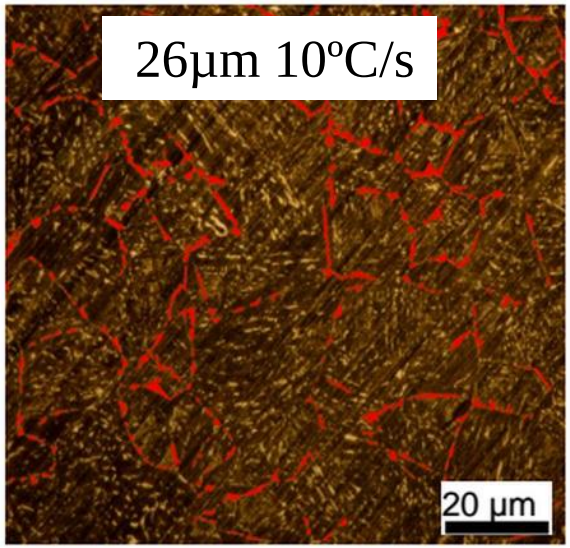
80µm Solution

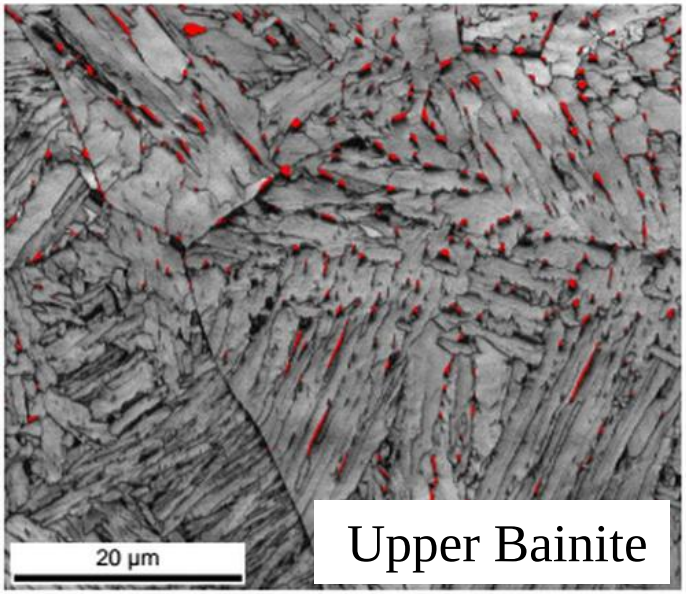


EVRAZ NSERC CRSNG TransCanada

Analysis on M/A constituent

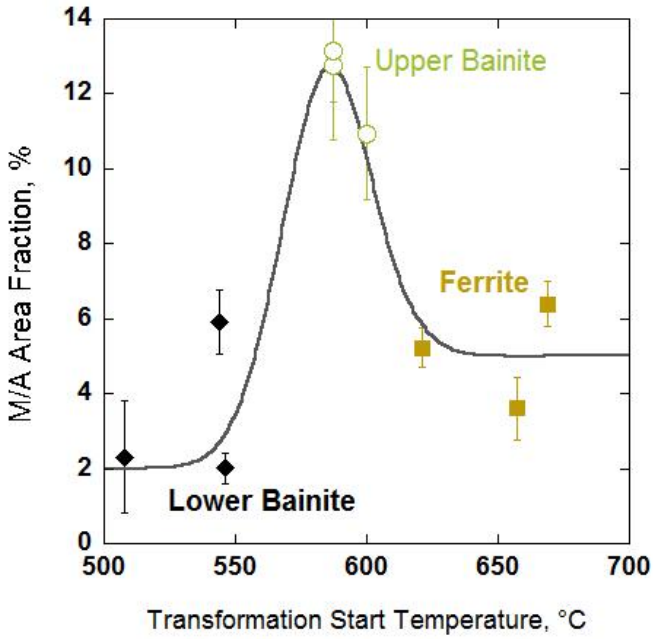
- M/A fraction were investigated by metallography and EBSD
- Relation between M/A fraction and microstructure class



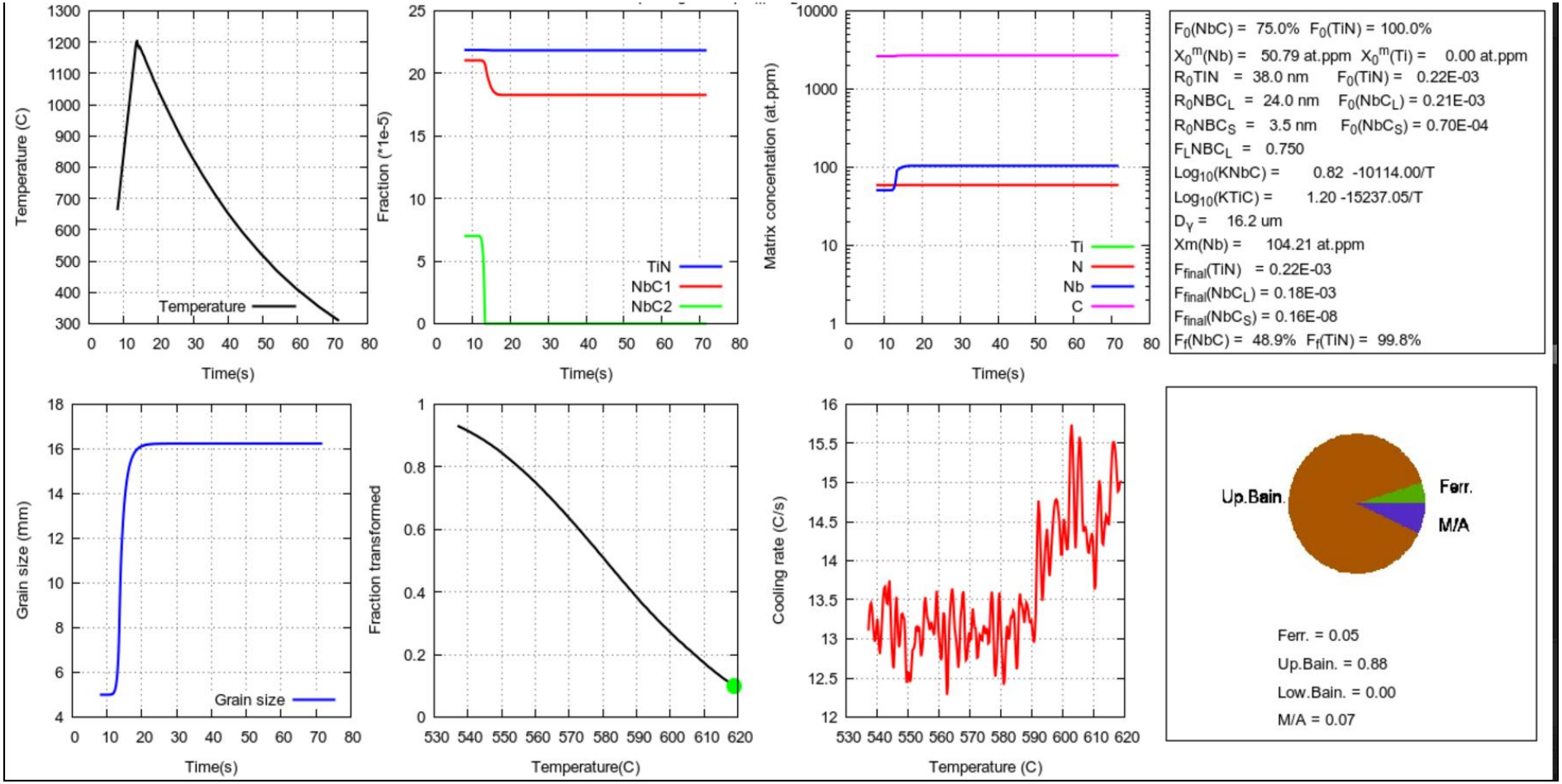


austenite – area fraction: 1.5 %

martensite



Quick view on results



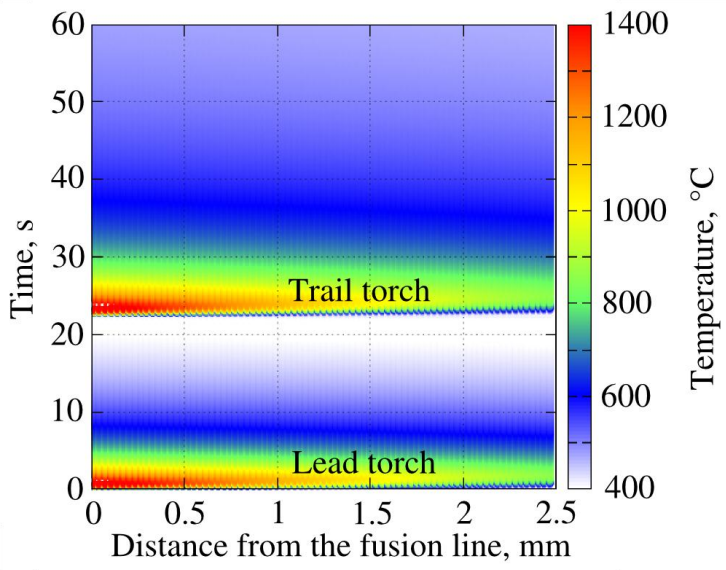
A simple temperature model

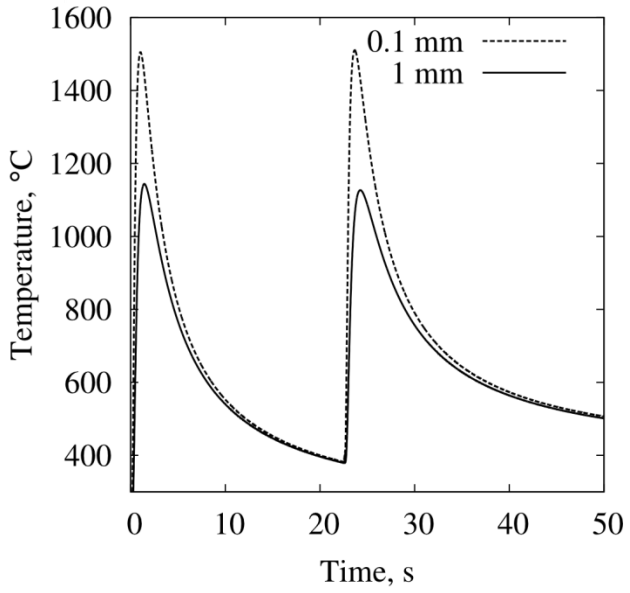
- Validate the predictive capability of the model for HAZ
- Rosenthal equation for thick plates

$$T(t,r) = T_0 + \frac{K}{t} exp\left(\frac{K}{et} \quad \frac{1}{T_{peak}(r) - T_0}\right)$$

- Renormalization for real welding scenario

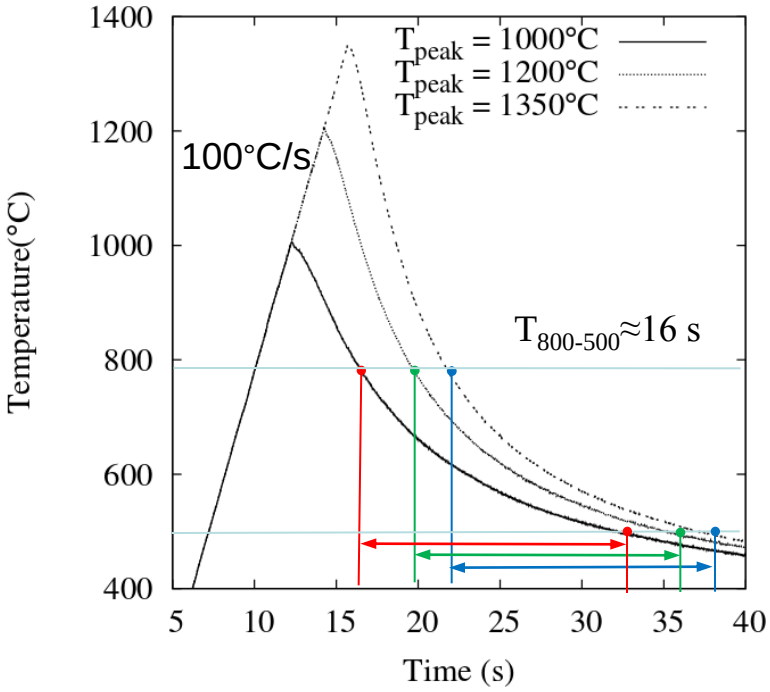
$$x(T_p) = x_{Rosenthal}(T_p)\frac{\lambda}{\lambda_{Rosenthal}}$$

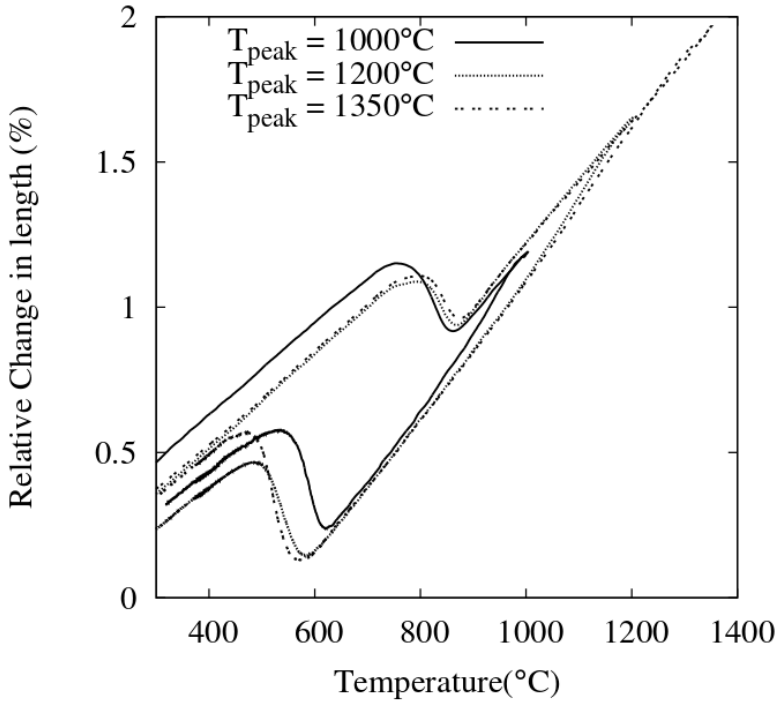




Model Validation during HAZ simulation

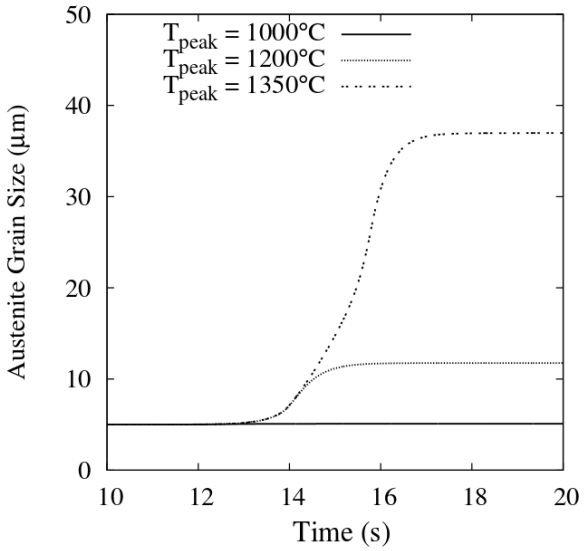
Three thermal cycles with different peak temperatures
Represent different position in the HAZ
Cooling rate in the 800℃ to 500℃ region is about 19℃/s



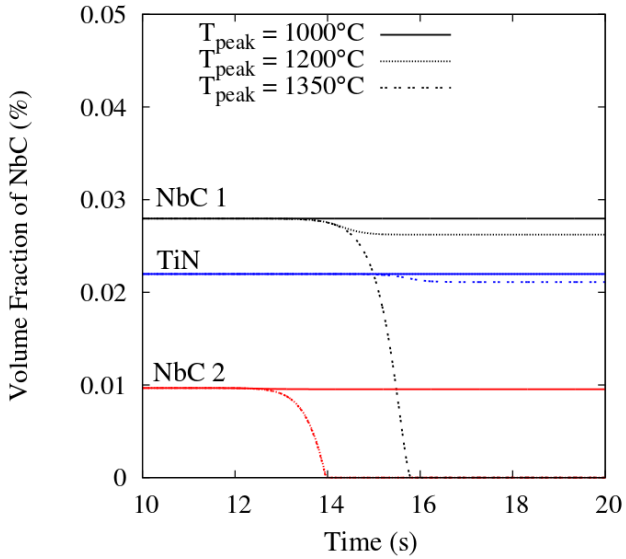


Model Validation during HAZ simulation

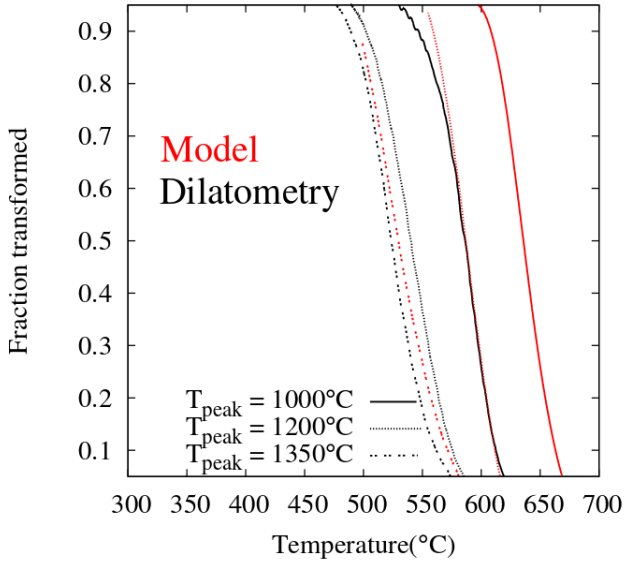
Austenite Grain Size



Precipitates



Fraction transformed



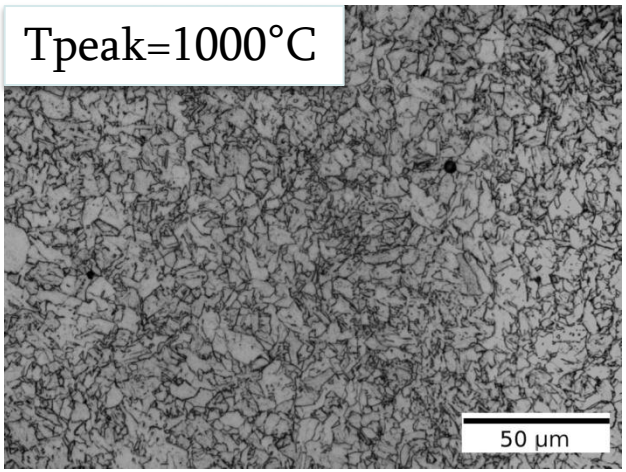
T_{peak} (°C)	C_{Nb} (at.ppm)	d_γ (μm)	T_S (°C)	B_S (°C)
1000	4	5	669	/
1200	62	12	616	616
1350	204	37	580	580

EVRAZ NSERC CRSNG TransCanada

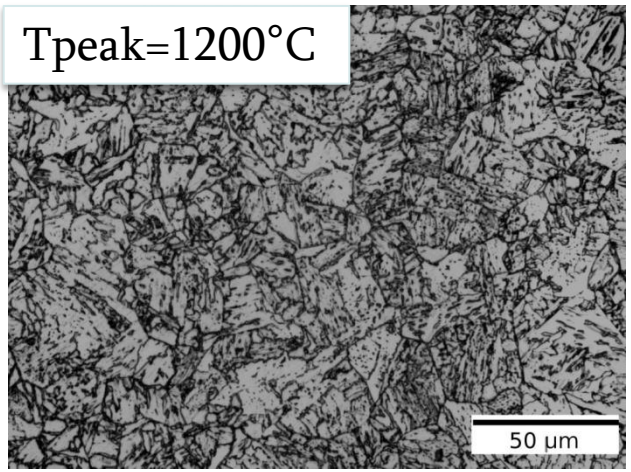
Prediction of transformation products

Experimental observations – Gleeble tests with different Tpeak

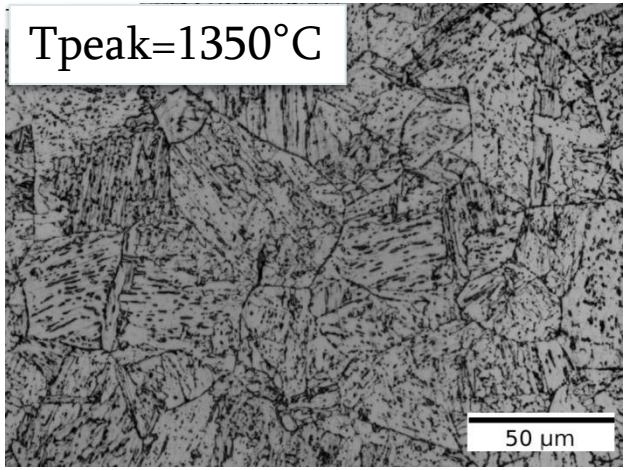
F=90%, B=0%, M/A=10%



F=0%, B=92%, M/A=8%



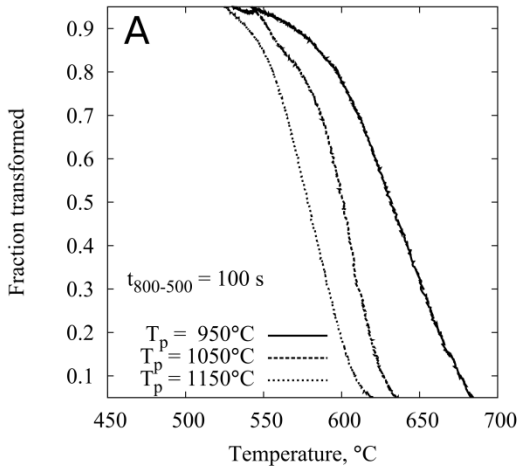
F=0% B=95%, M/A=5%

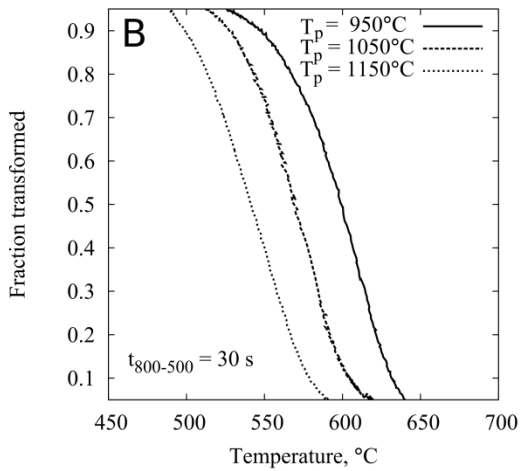


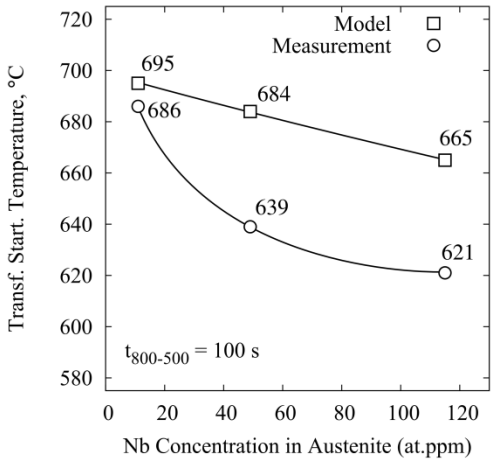
T_{peak} (°C)	Ferrite Fraction (%)	Upper Bainite Fraction (%)	Lower Bainite Fraction (%)	M/A Fraction (%)
1000	95	0	0	5
1200	0	84	0	16
1350	0	7	87	6

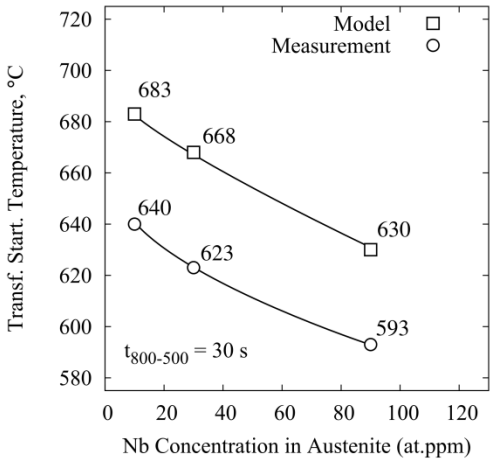
Transformation start temperature prediction

- Discrepancy in the cases where the precipitates are partially dissolved
- Possibly explained by an underestimation of the matrix concentration of Nb
- Challenge to evaluate the concentration of Nb in the to calibrate strength of the solute drag on the austenite decomposition



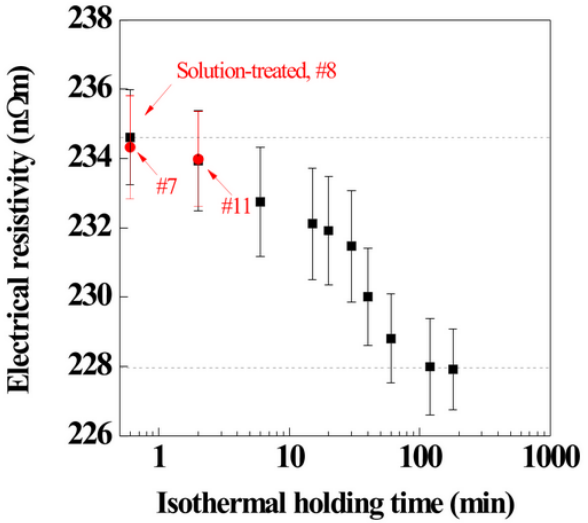


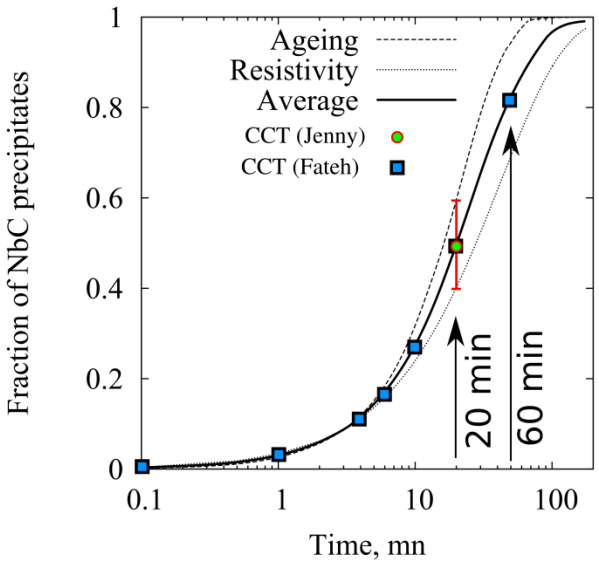




Precipitation kinetics of NbC precipitates

- Ageing experiments + Resistivity measurements in samples aged various times at 900C from the fully dissolved state.
- Adjustments to the initial fraction of Nb in the alloy
- Re-examination of the correlation between matrix concentration of Nb and solute drag during decomposition

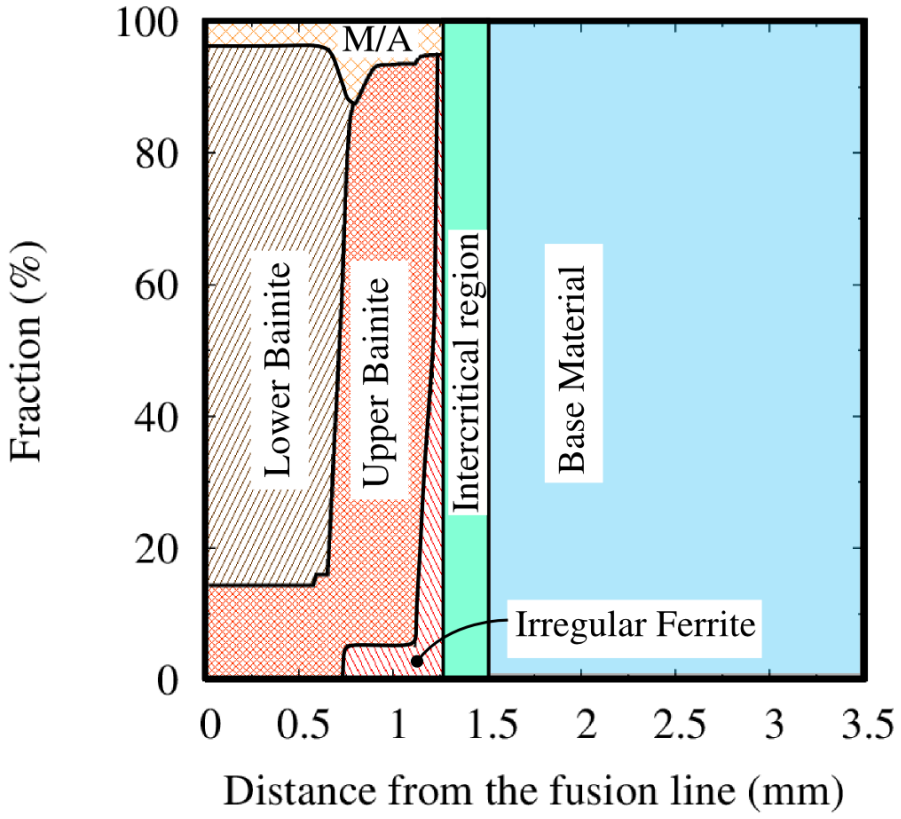




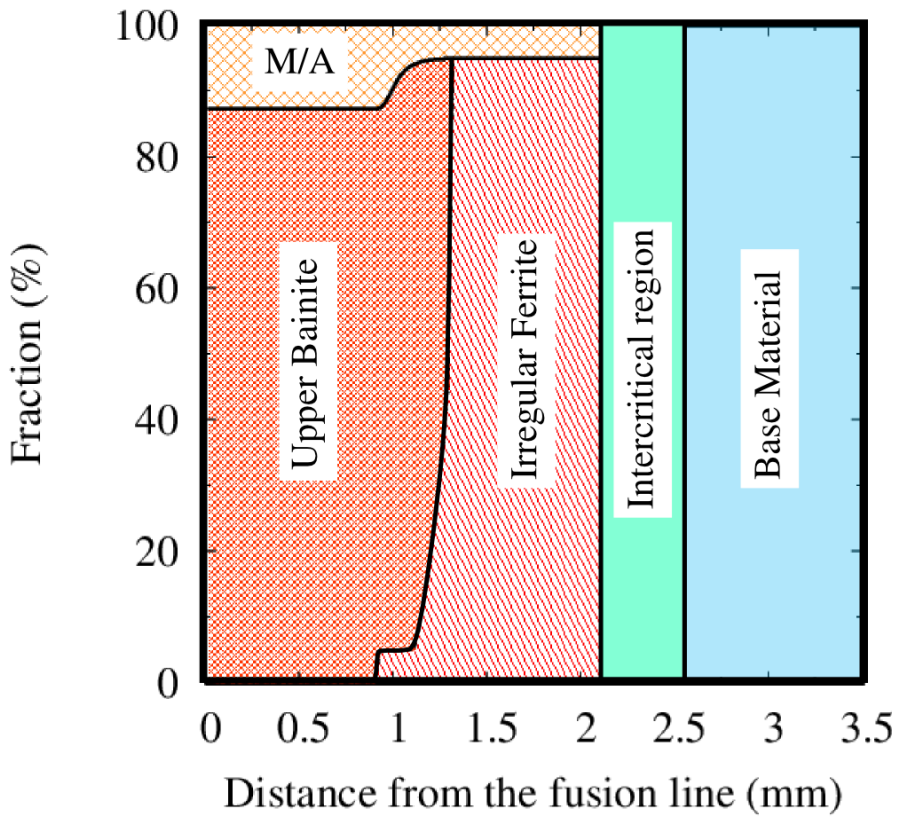
EVRAZ NSERC CRSNG TransCanada

Microstructure maps for welding scenario

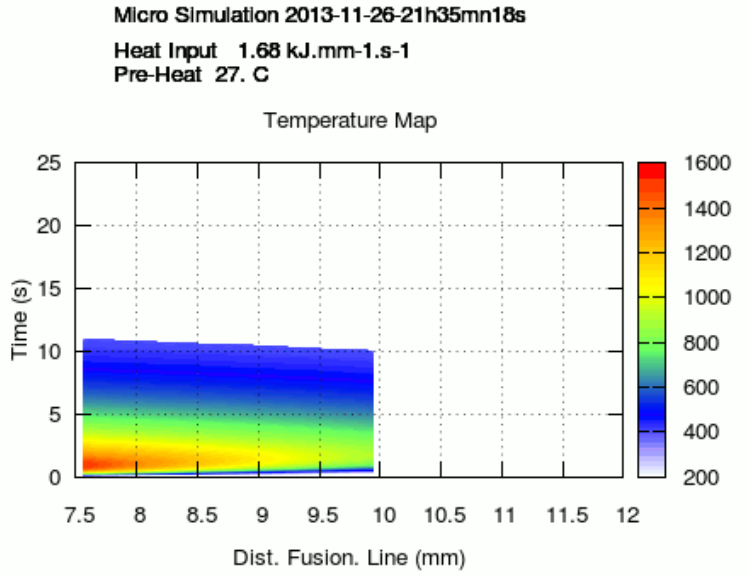
Single Torch GMAW Scenario

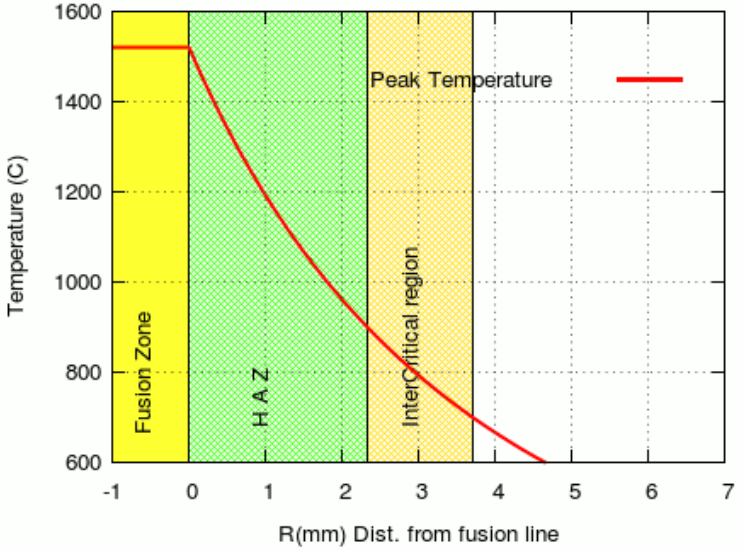


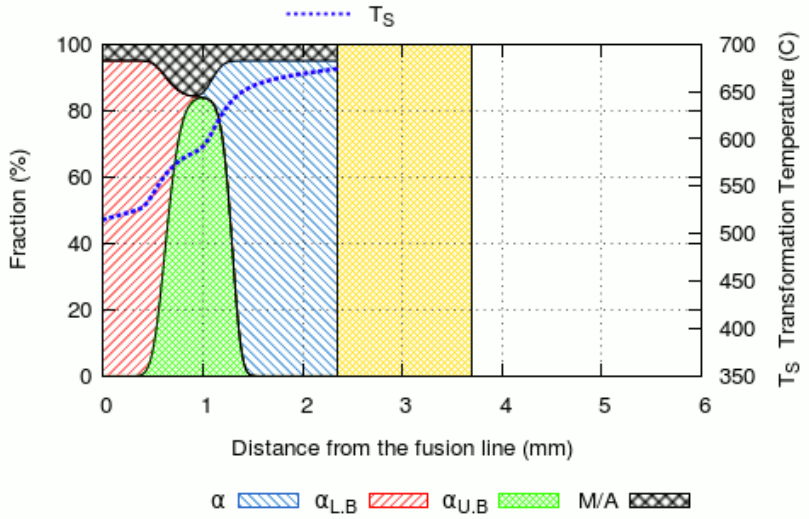
Dual Torch GMAW Scenario

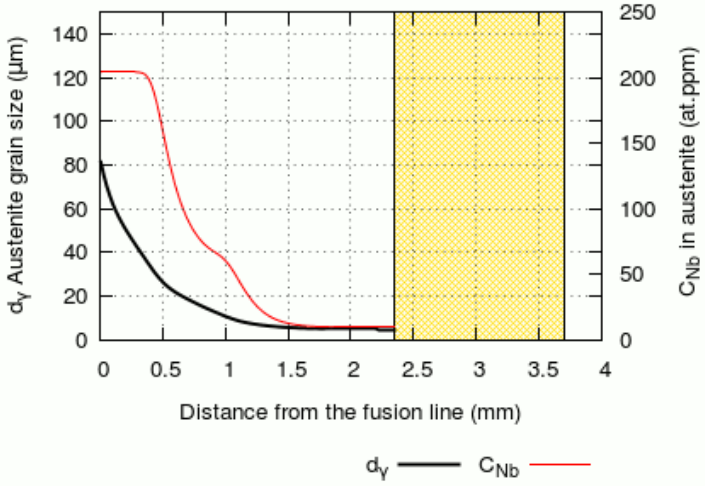


Influence of Pre-heat temperature









EVRAZ NSERC CRSNG TransCanada

Future works

- Validate the microstructure model for real HAZ simulation.
  - Austenite grain size
  - Austenite decomposition temperature/kinetics
  - Fraction of transformation products.

- Integrate quantitative criteria for bainite morphology discrimination
- Microstructure evolution in the intercritical region
- Relation microstructure-mechanical properties
- Extent to additional linepipe steel composition