Thermomechanical Model for Rolling and Cooling of Hot Rolled Steel Band

Aldo Lopez, Justin Proksa, Phil Norman, Yu Gao
Faculty Advisor: Professor Matthew J. M. Krane
Industrial Sponsors: Robert Ives, David Mix (USS)

Demand for thicker gauge steel for pipeline applications has increased, but thicker product gives non-uniform microstructures and properties. Large surface-to-center temperature gradients occur as the steel is rolled and the microstructure is transformed during laminar cooling. A thermomechanical model is developed to estimate the temperature profile through the steel band during hot rolling, quenching and coiling.

This work is sponsored by United States Steel Corporation, Gary, IN

Project Background

Increasing the gauge for line pipe applications has led to non-uniform grain sizes and mechanical properties through the band thickness after hot rolling and quenching. This observation is attributed to the increased temperature gradient through the thickness during laminar cooling. US Steel needed to evaluate their current hot rolling process and was seeking suggestions for process changes to reduce these metallurgical differences.

Goal

The goal is to extend the model of the hot strip mill at US Steel's Gary Works developed by a 2014 Senior Design group to estimate the temperature through the thickness of a steel band as it passes through the laminar cooling section and final coiler. The model estimates trends in through thickness thermal behavior and is used to suggest process changes.

Model Development

Computational Model

storage conduction generation

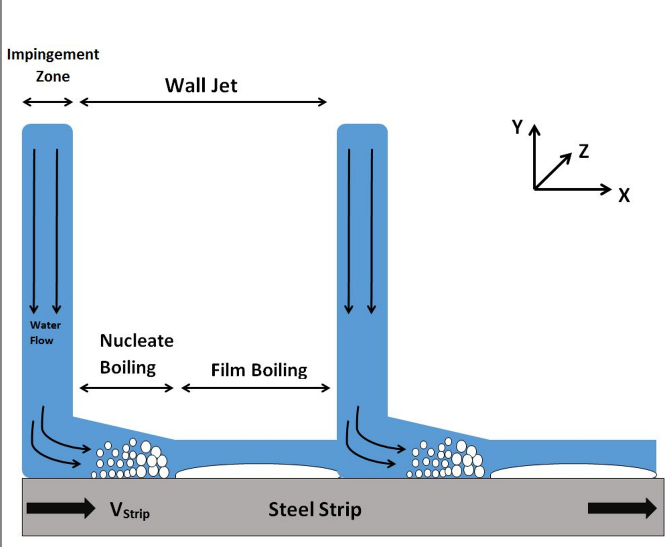
$$\frac{\partial(\rho c T)}{\partial t} = \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \dot{Q}$$

$$-k\frac{\partial T}{\partial y}\Big|_{CL} = 0$$

$$-k\frac{\partial T}{\partial y}\Big|_{surf} = h(t)(T - T_\infty)$$

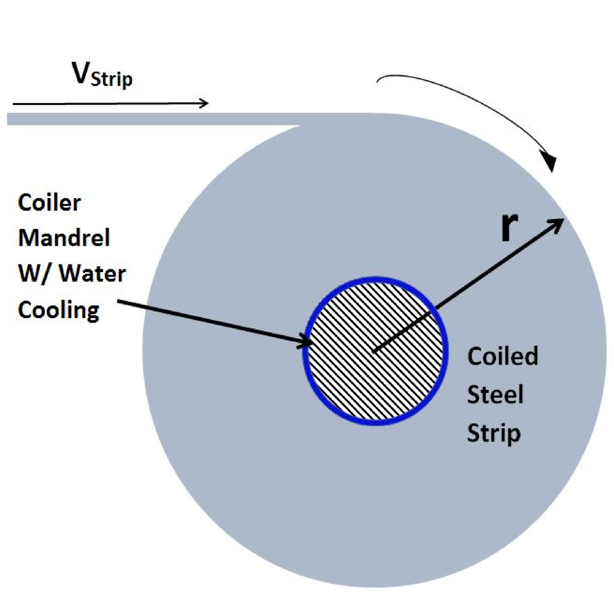
The implicit finite volume method was used to discretize the transient energy conservation equation. These equations were solved for temperature at each time step with the Gauss-Seidel method. The volume of each cell was held constant as its thickness decreased. The heat generation is due to plastic deformation during rolling.

Process Models

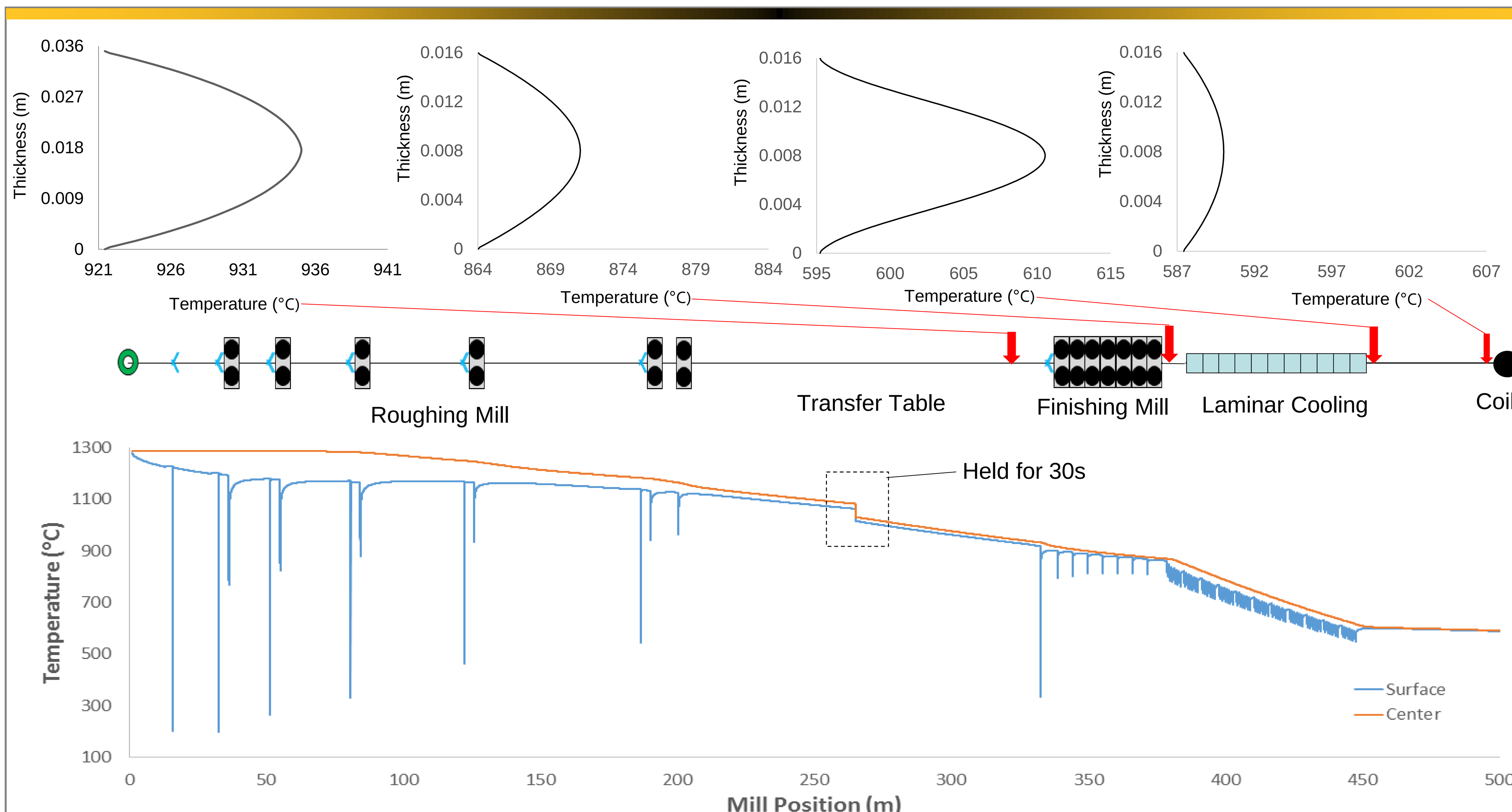


The laminar cooling bed quenches the steel (in the austenite phase) to the ferrite and cementite phases. Falling water impinges on the strip and undergoes nucleate, then film boiling.

The heat transfer coefficient on the strip is highest in the impingement zone due to high water velocity normal to the surface. Heat transfer first decreases in the wall jet zone, then increased due to nucleate boiling, followed by a drop due to the beginning of film boiling.

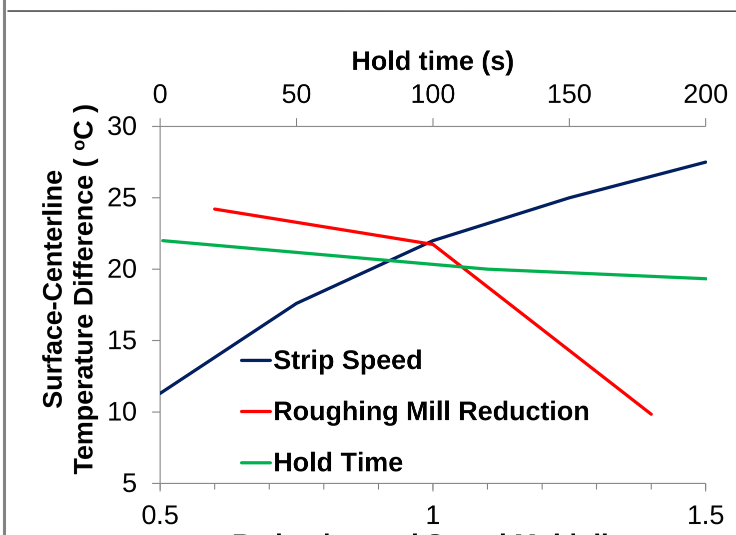


The final step gathers the steel strip (<1" thick at this point) into a transportable coil. Heat transfer is dominated by conduction between the steel coil and the water-cooled center coiler mandrel. Some heat is also lost by radiation to the environment.



Suggested Process Temperature History in the Hot Rolling Mill at US Steel Gary Works, Gary, Indiana
Temperature profiles at four positions illustrate how the temperature gradient changes throughout the hot mill. The surface and centerline temperature histories show the variation in temperature differences through the mill.

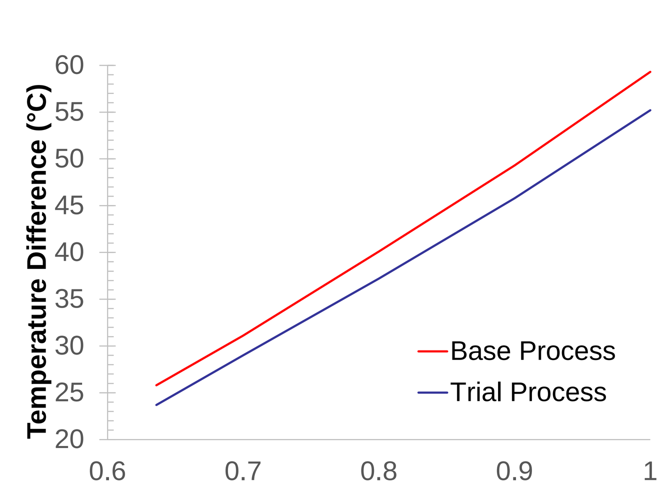
Sensitivity Study of Process Input Parameters



An analysis of the effects on thermal response of controllable process input parameters showed the surface to centerline temperature drop was more sensitive to roughing mill reduction and strip speed than hold time, for the practical ranges of these variables.

Model Trends

Surface-Centerline Temperature Difference After Laminar Cooling Bed



Based on the parametric study and the limits of mill equipment, we suggested a 12% roughing mill reduction increase and 60 second transfer table hold time. The predicted trend demonstrates that this process change should decrease the surface to centerline temperature difference from 3 to 5 ^oC after the laminar cooling bed.

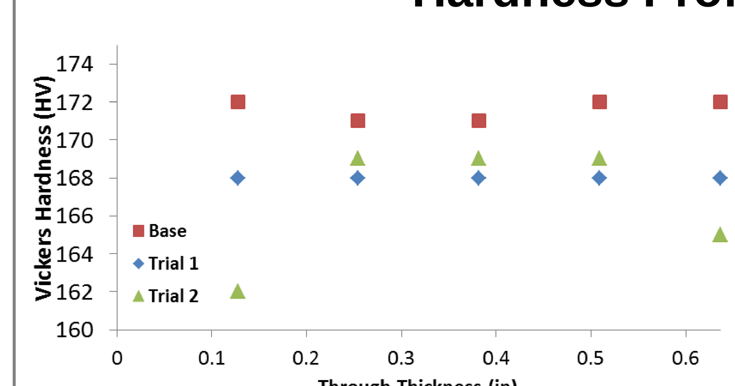
Process Recommendations

- US Steel should keep the strip speed during laminar cooling at the lowest possible speed to allow for maximum heat extraction through the center of the band.
- For 0.636" gauge steel, a 30 second hold time should be applied to the process with 7.6% increased roughing mill reduction to decrease through-thickness temperature differences. US Steel ran this case for Grade 50 steel in the hot strip mill (Trial 2).
- For thicker gauge steel, a 60 second hold time and 12% roughing mill reduction increase should be applied to reduce the through-thickness temperature difference.

Plant Results

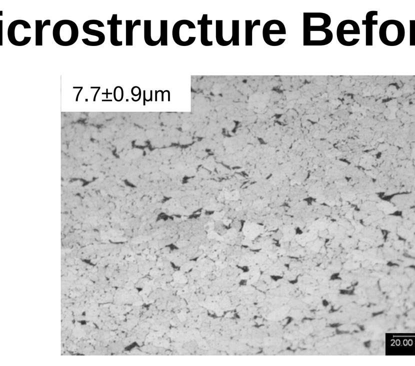
U.S. Steel ran three trials at their Gary Works hot strip mill. The trials consisted of a standard process trial, and two trials with variations of the suggested process changes.

Hardness Profile



Trial 1: Increased transfer table hold time to 30 seconds with no roughing mill reduction increase.
Trial 2: Maintained 30 second hold time and increased roughing mill reduction by 7.6%.

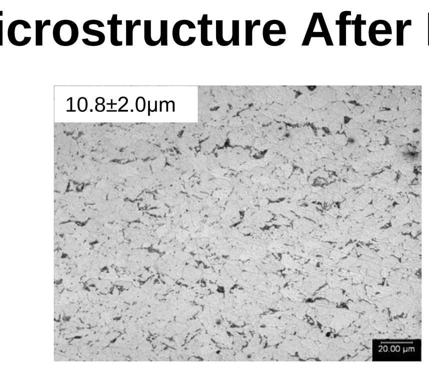
Microstructure Before Process Suggestion (Base)



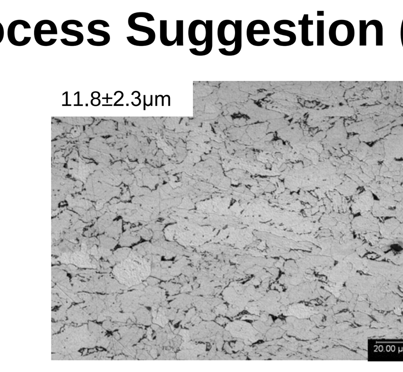
Surface

Centerline

Microstructure After Process Suggestion (Trial 2)



Surface



Centerline

Trial 2 produced larger overall grains with increased size variation. The overall hardness profile of trial 2 is lower with greater variation compared to the base case.

Conclusions

- For 0.636'' gauge steel, process suggestions increased grain size and decreased hardness uniformity, therefore the standard process should be maintained.
- As the steel gauge increases, lower strip speed, longer hold time and more reduction reduce the through-thickness temperature difference.
- Process suggestions should be tested on larger gauge steel band to evaluate effect on final microstructure and mechanical properties.