Modeling of Thin-Slab Hot Rolling Technologies

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The continuous improvement of hot strip rolling technology and the development of new steel grades make it necessary to use specialized models of hot rolling mills in order to successfully produce high-quality products. Examples of such technologies can be Compact Strip Production (CSP® by SMS group), Endless Strip Production (Arvedi ESP by Primetals Technologies) and Quality Strip Production technology (QSP® by Danieli). Moreover, the availability of such models makes it possible to accelerate the testing of new steel grades through virtual trials. Virtual trials allow saving costs in the process of finalizing steel composition. This article summarizes successful experiences of United States Steel Corporation in development such models and their usage.

Introduction

To assist the Gary Works 84-inch hot strip mill in optimizing mill operations and analyzing equipment changes or proposed improvements, a computer program, BARTEMP, was developed at the U. S. Steel Research and Technology Center between 1980 and 1983. Initially, BARTEMP was intended only to predict the transient, through-thickness (1D) temperature distribution in the middle of the bar width, at any arbitrarily chosen location along the bar length (using Lagrangian coordinates), from reheat furnace dropout to the coiler entry. The program could handle any integrated mill layout, including reversing and tandem roughing stands, and it could account for head-to-tail temperature variations along the bar length.

Between 2016 and 2019, the U. S. Steel Research and Process Innovation groups developed a new version, a thermomechanical microstructural (TMM) model.[1] The TMM model supports all the features that were available in BARTEMP. In addition, the following capabilities were added: (a) calculations of the transient, through-thickness temperature distribution from side to side across the bar width (2D); (b) calculations of rolling force, torque, and power in the roughing and finishing stands; (c) evaluation of the austenite decomposition during the laminar water cooling on the runout table and during post-rolling air cooling of the hot-rolled coil; and (d) prediction of the mechanical properties, i.e., yield strength (YS), ultimate tensile strength (UTS), from head to tail and from side to side of the hot-rolled strip.

Recently the TMM model has been further developed to include thin-slab rolling technologies, such as Compact Strip Production (CSP® by SMS group) and Arvedi Endless Strip Production (ESP by Primetals Technologies).

The TMM model uses the actual layout (dimensions and spacing) of a particular hot mill. The input files contain the following information: (1) slab steel grade and dimensions; (2) roll diameters, speed, and drafts in the roughing (if present) and finishing stands; (3) position of the heat retention panels, i.e., “closed” or “opened” if they are present; (4) water flows through the banks in the laminar cooling section.

This article presents the results of checking the new prediction capabilities and the accuracy of calculations of loads in rolling stands and the mechanical properties of hot-rolled strips produced on thin-slab rolling mills.

Results and Discussion

Two classes of steels were chosen for testing: low- to medium-carbon and high-strength low-alloyed (HSLA). To compare the measurement results with the calculated data, six low- to medium-carbon grades, as well as 15 HSLA grades, were selected. The scope of simulations is summarized in Table 1.

Table 1

The Scope of Simulations

Low- to medium-carbon steels	High-strength low-alloy steels
Main elements	
Carbon – 0.045% to 0.263% Mn – 0.35% to 1.3% Si – 0.0175% to 0.235%	Carbon – 0.046% to 0.055% Mn – 0.593% to 1.46% Si – 0.022% to 0.329% Nb/Cb – 0.001% to 0.052% V – 0.003% to 0.065% Ti – 0.001% to 0.142 Mo – 0.011% to 0.147%%
Products size and coiling temperature range	
Gauges – 0.06 to 0.50 inch Widths – 48.5 to 74.6 inches Coiling temperature – 944°F to 1,205°F	Gauges – 0.077 to 0.800 inch Widths – 48.5 to 74.4 inches Coiling temperature – 961°F to 1,245°F

Comparing the Measured and Predicted Data for a CSP Hot Mill

The results of comparison of rolling forces for both classes of steel are shown in Fig. 1. In general, good agreement between the measured and calculated forces is observed. The maximum difference does not exceed ±10%. For the off-line open-loop prediction, in the absence of adaptation, this can be considered acceptable accuracy.

Comparison of yield strength (YS) and ultimate tensile strength (UTS) shows results similar to rolling forces (Figs. 2 and 3). The maximum difference does not exceed ±10%. Likewise, for open-loop prediction, in the absence of adaptation, and accounting for certain "noise" in the measured data, this can be considered acceptable accuracy.

Figure 1

Comparison of measured and calculated rolling forces (low- to medium-carbon and high-strength low-alloy steels) in stands 1–6.

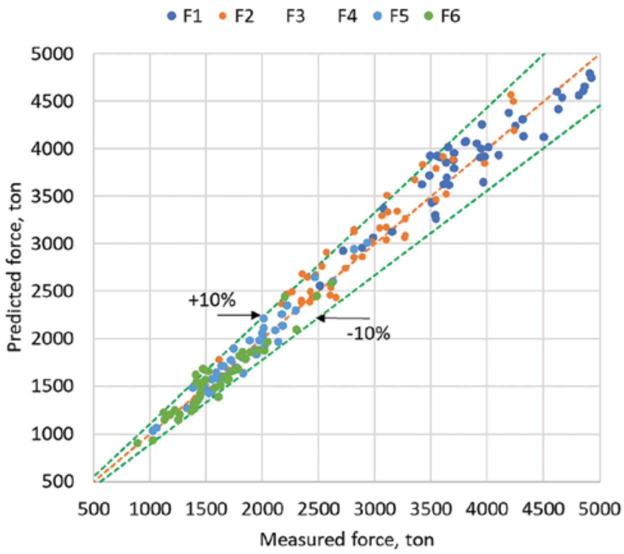


Figure 2

Comparison of measured and calculated yield strength.

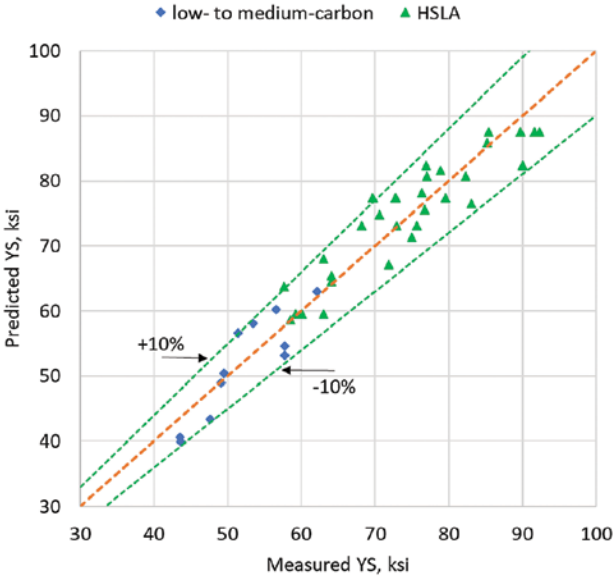


Figure 3

Comparison of measured and predicted tensile strength.

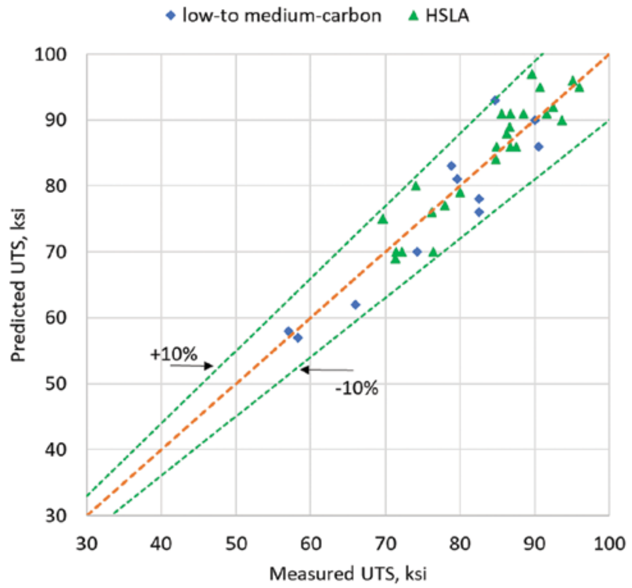
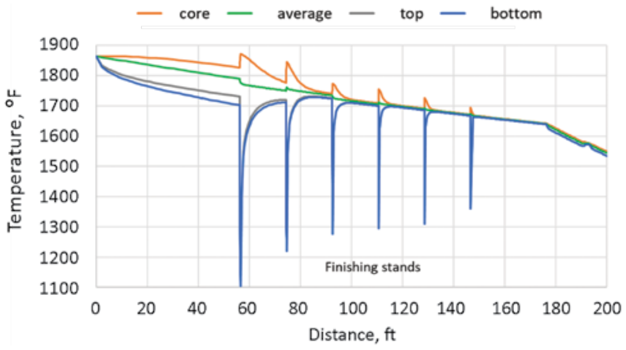


Figure 4

Bar temperature development through CSP hot mill.



Some Results of a HSLA Grade Simulation

Figs. 4–6 present some results of rolling simulation of a HSLA steel. The charts show bar temperature development, rolling forces and motor power with their limit values, as well as the minimum required gap time between successive bars.

Also, Fig. 7 presents the amount of retained strain after each pass through the finishing stands.

The model allows for the simulation of austenite decomposition during the laminar cooling of the strip on the runout table and during the following air cooling. Kinetics equations for isothermal cooling condition that was assumed for air cooling were developed and integrated into the TMM model. An example of the isothermal cooling simulation is presented in Fig. 8. Two cooling paths are shown, one for the outer laps of the coil (coil OD) and the other for the body of the coil. Because the outer laps cool faster than the middle laps, they can transform to a ferrite–pearlite–bainite microstructure, while the middle laps still develop a ferrite–pearlite microstructure. The importance of these results is that they clearly demonstrate the formation of high-strength laps on the inner

Figure 5

Predicted rolling forces, high-strength low-alloy (HSLA) steel.

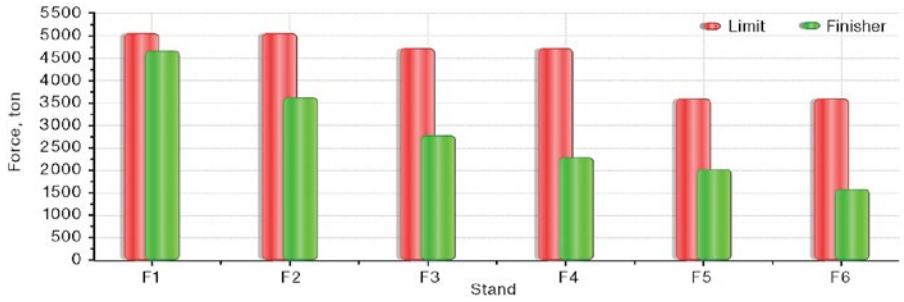
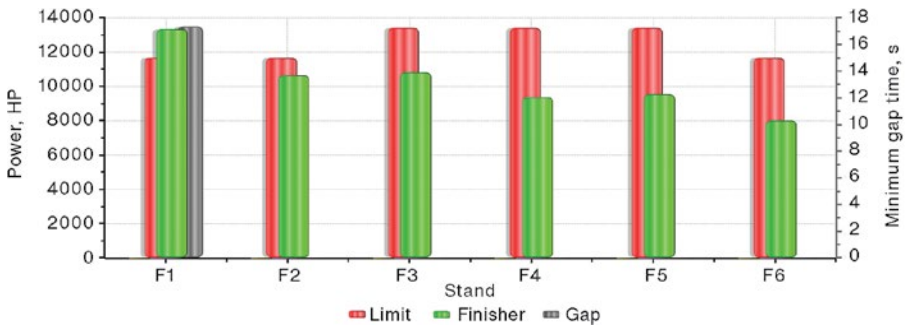


Figure 6

Predicted motor power and gap time, HSLA steel.



diameter and outer diameter of coils of high-strength steel, which are often observed in practice.

Fig. 9 presents an example of one of the simulation resulting screens, i.e., temperature distribution in the mid-plane of the coil of a medium-carbon steel after 72 hours of air cooling. The material YS, UTS and phases are also displayed.

The model makes it possible to evaluate the various influences of processing parameters; for example, the effect of coiling temperature on the strength of hot-rolled strips. Fig. 10 shows the variation of UTS as a function of coiling temperature for medium-carbon and HSLA steels. The effect of precipitation hardening is clearly visible for HSLA steel.

UTS in Fig. 10 was calculated for the average coiling temperature of the hot-rolled coil. Since the model calculates the strip temperature from head to tail and across the width, it makes it possible to obtain a three-dimensional map of the strength distribution. Such maps are shown in Figs. 11 and 12. The data presented in them belong to two different steel grades, HSLA and AHSS, coiled at 1,100°F. The impact of chemical composition is obvious — HSLA steel demonstrates the effect of precipitation hardening, while AHSS steel shows the effect of accelerated cooling of the strip edges and extremities.

Figure 7

Predicted amount of retained strain, HSLA steel.

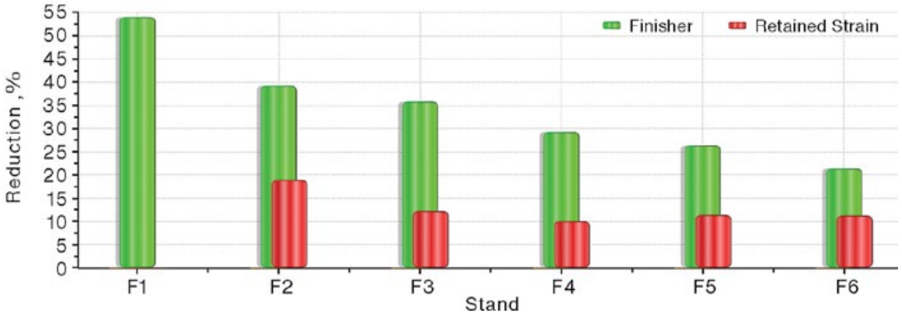


Figure 8

Time-temperature-transformation (TTT) diagram and the cooling paths of middle and outer laps of a hot-rolled coil of advanced high-strength steel (AHSS).

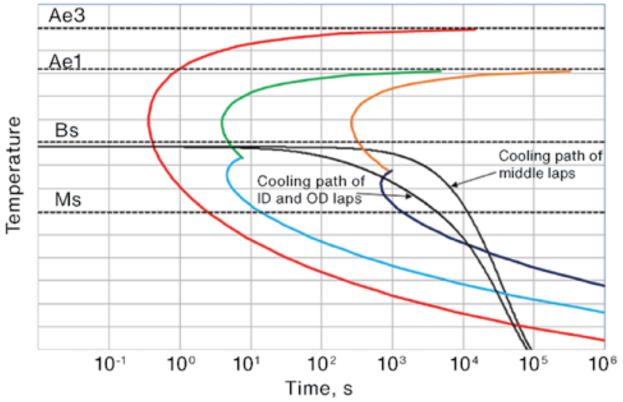
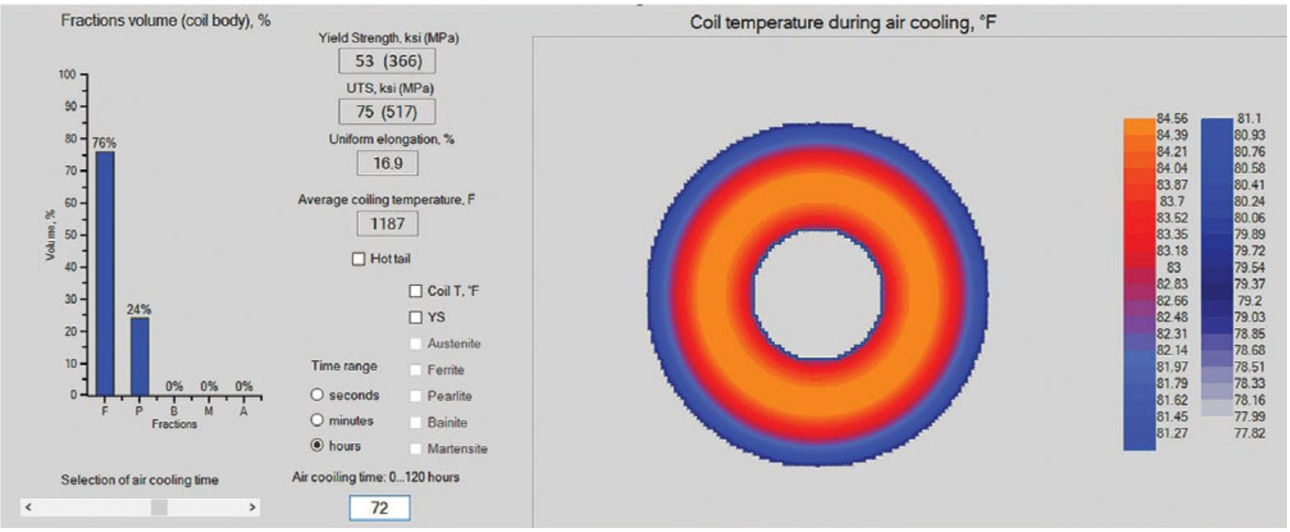


Figure 9

Temperature distribution in the mid-plane of the coil of medium-carbon steel after 72 hours of air cooling.



Yield Strength, ksi (MPa)
53 (366)

UTS, ksi (MPa)
75 (517)

Uniform elongation, %
16.9

Average coiling temperature, F
1187

☐ Hot tail

☐ Coil T, °F
☐ YS
Austenite
Ferrite
Pearlite
Bainite
Martensite

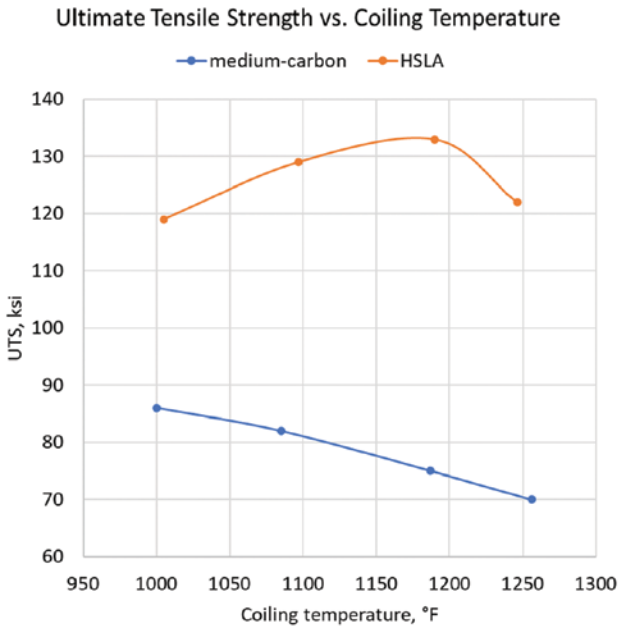
Time range
○ seconds
○ minutes
● hours

Selection of air cooling time

Air cooling time: 0...120 hours
72

Figure 10

Predicted ultimate tensile strength (UTS) for two steel grades.



Simulation of an ESP Hot Mill

The TMM model was successfully tested for an Endless Strip Production (ESP) hot mill. Fig. 13 displays the bar temperature development for one of the known ESP configurations. A noticeable difference in the initial cross-sectional temperature distribution can be observed between CSP and ESP processes, Figs. 4 and 13. The presence of tunnel furnace helps to make temperature distribution more uniform.

Figure 12

3D map of UTS, AHSS grade.

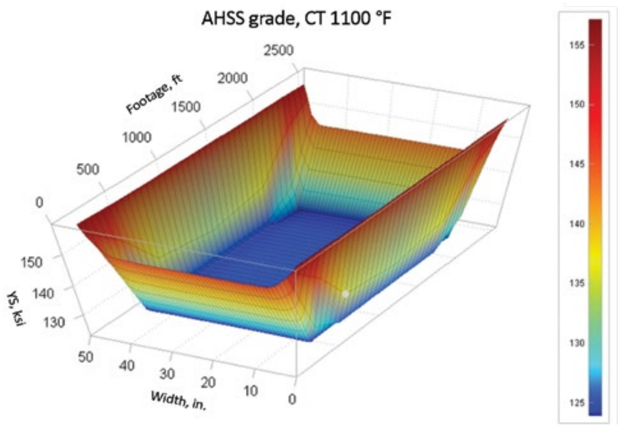
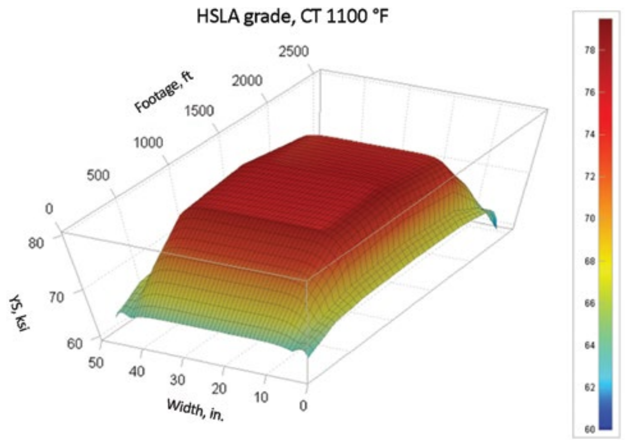


Figure 11

3D map of UTS, HSLA grade.

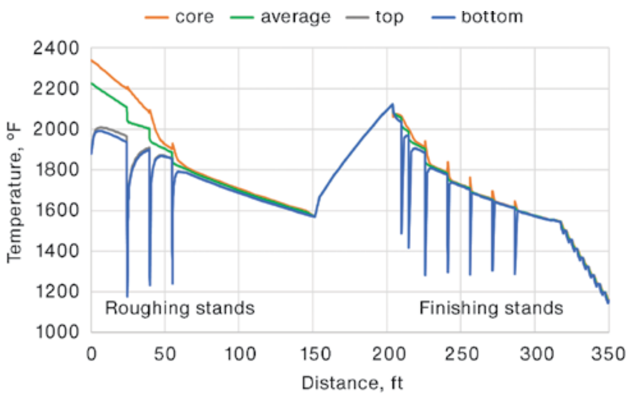


Summary and Conclusions

For several years, the thermomechanical-microstructural model serves as a primary tool for assessing the capabilities of hot rolling in the integrated mills to successfully produce various steel grades, including HSLA and AHSS, with prime quality and maximum productivity. Recently, the TMM model capabilities have been further developed to include simulations of thin-slab rolling. Testing of the accuracy of the model predictions for low- to medium-carbon and HSLA steels showed good agreement between the measured and calculated data. The model allows to simulate various "what-if" scenarios in virtual trials for the integrated hot strip mills as well as for thin-slab rolling configurations.

Figure 13

Temperature development through ESP hot mill.



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Reference

1. E. Nikitenko, "Benefits of Usage of Various Models in a Hot Strip Mill," *AISTech 2023 Conference Proceedings,* 2023, DOI: 10.33313/387/155.

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