Simulation and Development of Advanced High Strength Steels on a Hot Strip Mill Using a Microstructure Evolution Model

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Abstract

In order to meet the needs of their customers, steel makers are striving to make a variety of new grades of steel with higher strengths and more complex microstructures. Advanced High Strength Steels (AHSS) are required to meet new applications. Steel companies need to be able to develop these new steels in a cost-effective way and get them to market as fast as they can while manufacturing them within the constraints of their mill configuration. Lake Erie Steel (A Stelco Company) was able to successfully develop an AHSS with the aid of the INTEG Hot Strip Mill Model (HSMM). The HSMM effectively modeled the low coiling temperatures required for Hot Rolled Dual Phase steel. The HSMM enabled Lake Erie Steel to develop an initial rolling mill schedule, including the spray bank set-up for the run out table, and reduce the number of trials needed and correspondingly the cost of mill time.

Introduction

In today’s rapidly changing global economy, steel industries around the world are striving to meet the needs of the marketplace. One common theme is the need for lighter and stronger steels for new and existing applications. The automotive industry, in particular, faces many challenges, including the need to reduce fuel consumption and increase safety. New grades of highly formable AHSS are being developed that will continue to meet these
demands (Figure 1) [1]. The challenge for steelmakers is how to develop these AHSS in a cost effective way, be able to produce the product within their current mill configuration, and get the product to market as fast as possible. One steel company, Lake Erie Steel GP Inc. (A Stelco Company) is utilizing an advanced hot strip mill simulation model to reduce their development cost and time to bring AHSS, such as Hot Rolled Dual Phase (HRDP), to market. As shown in Figure 1, DP steels move further along the strength curve, beyond conventional high strength steels. The INTEG Hot Strip Mill Model (HSMM) effectively calculates the unique cooling path needed for AHSS in low temperature ranges not typically seen on a hot strip mill.

It is not only imperative to acquire the proper mechanical properties of a newly developed grade of steel, but to also reduce any productivity constraints while upholding a high level of repeatability. There are many phases of developing a new Hot Rolled Dual Phase (HRDP) grade with a number of challenges and restraints. Typically, a series of process trials must be performed to acquire the correct temperature regime and in turn the needed mechanical properties through trial and error. HRDP also requires an uncommon cooling trajectory in order to obtain the dual phase (ferrite and martensite) microstructure at a very low (<150°C) coiling temperature. Another approach to accurately attain the microstructure transformation of the steel grade is to develop the continuous cooling transformation (CCT) curve for a specific chemistry. The CCT curve outlines the extent of transformation as a function of time for a continuously decreasing temperature. Since obtaining the grade’s CCT curve is time consuming and very expensive, one must rely on process trials with the assistance of a predictive model such as the HSMM. The use of the HSMM was beneficial in reducing the number of trials needed and providing vital information on the relationship between the process parameters and the strip cooling trajectory.
Microstructure Model

The INTEG Hot Strip Mill Model (HSMM) is an off-line, PC-based model that is capable of simulating steel rolled on a hot strip mill or plate mill [2]. The model calculates the temperature evolution, rolling forces, microstructure evolution and final mechanical properties. A user-friendly interface is provided, enabling the user to configure a variety of rolling mills, including reversing or continuous roughing mills, heat retention panels or coil-boxes, continuous finishing mills, Steckel mills, run out tables, and coilers or cooling tables. A variety of steel grade families can be modeled, including plain carbon, High Strength Low Allow (HSLA), Interstitial Free (IF) and Dual Phase (DP) steels. An advanced feature, called Grade Builder, allows the user to view and modify the coefficients and algorithms used for the microstructure calculations. Grade Builder provides flexibility and the ability for each user to conduct advanced, proprietary grade development activities.

After the steel slab is discharged from the reheat furnace, the processing in a hot mill can be subdivided into two principle stages: rolling (in both the roughing and finishing mill), and cooling (water cooling on the run-out table and coiling/cooling bed). The metallurgical phenomena, which occur in these two steps, are summarized in Table 1.

<table>
<thead>
<tr>
<th>Process Step</th>
<th>Metallurgical Phenomena</th>
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<tbody>
<tr>
<td>Rolling</td>
<td>recrystallization, austenite grain growth, precipitation</td>
</tr>
<tr>
<td></td>
<td>austenite decomposition, precipitation strengthening, phase transformation</td>
</tr>
<tr>
<td>Cooling</td>
<td></td>
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</table>

Modeling the austenite decomposition on the run-out table and subsequent precipitation of carbides, nitrides, and/or carbonitrides in ferrite during coiling are of particular importance. Both aspects essentially determine the mechanical properties, which depend on the character of the transformation products (ferrite, pearlite, bainite, and martensite), the ferrite grain size, and the extent of precipitation and solid solution
strengthening. However, for AHSS, proper modeling of the cooling on the run out table (ROT) is also of extreme importance due to the low coiling temperatures required to achieve the desired microstructure and final mechanical properties. These low coiling temperatures can be as low as 100°C and are well below the normal coiling ranges (550 – 720°C) for most steels typically produced on a hot mill.

The INTEG HSMM has a very detailed model for calculating the heat transfer on the ROT and is capable of handling low coiling temperatures. The model breaks down each header (spray) into 6 zones (Figure 2). Within each of these zones, various boiling phenomena occur as the strip temperature drops and the boiling phase goes from film boiling to transition boiling and finally nucleate boiling (Figure 3). During each of these stages, the amount of heat transferred between the strip and the water varies and as such, the model calculates a variety of heat transfer coefficients for each surface node on the strip based on the node’s location on the ROT.

Once the strip temperature drops below approximately 400°C (Superheat temperature), a phenomenon known as the Leidenfrost effect occurs. The Leidenfrost effect basically explains how a water drop is long lived when deposited on metal that is much hotter than the boiling temperature of water and was given this name because it was first studied by
Johann Gottlob Leidenfrost in 1756 (although his work was not translated until 1965 and then became more widely read). In a study done by Walker [3], the Leidenfrost point (Figure 4) was determined as the point at which the water drop lasts the longest. Drops on a surface at or above this temperature are actually boiling and creating a vapor preventing the water from effectively spreading out and transferring more heat from the metal to the water. Drops on a surface below this value tend to spread out over the surface and rapidly conduct energy from the surface thus cooling it faster. On a hot strip mill run out table this same effect occurs when coiling the steel to low temperatures. Once the strip has successfully dropped below approximately 400°C (superheat temperature), the later banks of sprays have a much greater ability to transfer more heat from the strip (higher heat transfer coefficients).

Work done by INTEG and subsequently by the University of British Columbia (UBC), analyzed this effect on data from two different run out tables from two different hot strip mills [4]. Both mills rolled steel that was coiled well below the Leidenfrost point. As a result of this work, INTEG has implemented two methods for handling the Leidenfrost effect in the HSMM, one developed by INTEG and one developed by UBC. The method developed by INTEG introduced the Leidenfrost Multiplier. The concept involves increasing the amount of heat flux in the nucleate boiling region in the impingement zone of each ROT spray. The resultant curve creates the maximum in the region of the critical heat flux (approximately the Leidenfrost point).

The model used in the HSMM for transition boiling follows the assumption by Berenson [5] that boiling in this region is a combination of unstable nucleate boiling \( q_{\text{nucl}} \) and unstable film boiling \( q_{\text{film}} \). The original form of Berenson’s model is multiplied by the Leidenfrost multiplier, \( LM \), as shown in equation (1). The contribution of each term in equation (1) depends on the fraction of the liquid-solid contact area, \( F \). In the HSMM, the

![Figure 4 – Water drop lifetimes on a hot plate from Walker [3]](image-url)
nucleate boiling heat flux is calculated using the macrolayer evaporation model, published by Pasamehmetoglu et al. [6] and modified by Hernandez [7] for the case of jet impingement and is shown in equation (2). The film boiling is calculated by using the correlation of Ishigai et al. [8] and the addition of the radiation heat transfer, equation (3). The result is the nucleate boiling heat flux in the impingement zone shown in equation (4). Note that equation 4 is the same as equation (1) when F = 1.

\[
q_{TB} = \left[ q_{me}F + q_{film}(1 - F) \right]LM
\]  
\text{(1)}

where
\[
q_{me} = \left(2m_{tp}i_{fg} \sqrt{\pi A_{yw}117.1 \cdot \Delta T_{sat}} \right)^{1.33}
\]  
\text{(2)}

and
\[
q_{film} = 5.4\left(1 + 0.527\Delta T_{sub}\right)u_{j}^{0.607} + 0.75q_{rad}
\]  
\text{(3)}

and
\[
q_{nucl} = q_{me} \cdot LM
\]  
\text{(4)}

By adding the ability to the HSMM to be able to predict low coiling temperatures, the HSMM has been able to help steel companies effectively model new steels such as dual phase. The user is able to conduct a what-if analysis and simulate a variety of rolling speeds, spray patterns and interrupt times to generate good starting points prior to mill trials.

**Dual Phase Development and Results**

Advanced High Strength Steels such as Hot Rolled Dual Phase (HRDP) are increasingly being considered for the use in automotive structural parts such as wheels and frames. HRDP steels consist mainly of a ferritic matrix with a dispersion of a hard martensitic second phase. The soft ferrite structure is fairly continuous, and thus provides high ductility. A minimum amount of martensite (4-5%) is required to obtain the mechanical properties typical for DP steels: a continuous yielding, a low yield to tensile strength ratio (YS/TS), a high uniform and total elongation, and high work hardening rates [9,10].
The base alloy for Lake Erie Steel (LES)’s thermomechanical approach was a low C-Mn structural steel with the proper addition of hardenability elements to suppress pearlite formation and promote martensite formation at a low cost [11,12]. The general thermomechanical approach consisted of a low finish rolling temperature (FT) followed by a stepped cooling path and a low coiling temperature (CT). The intent of this cooling trajectory is to form a two-phase ferrite and austenite microstructure during the interrupted temperature (IT) and then the carbon-enriched austenite is transformed to martensite during the final rapid cooling.

Since the formation time for polygonal ferrite is critical at the interrupted temperature in obtaining the desired mechanical properties for DP, the cooling trajectory was analyzed in terms of interruption time and FM exit (FMX) speed for a given gauge and ROT bank configuration. This step in the product development was important since it gave an insight on how to modify the interruption time within the same coil by employing multiple cooling configurations with a fixed FMX speed. Through the use of the HSMM, cooling capability curves were obtained as seen in Figure 5. These curves outline the different ROT bank configurations that can be utilized for a given FMX speed and gauge. As the configurations of the ROT change, the interrupted time will also change within the simulated temperature ranges (i.e. 800-900°C FT, 600-700°C IT, <150°C CT).

LES ran a series of trials with high carbon coils rolled at gauges ranging from 3-7mm to calibrate/validate the HSMM prior to trialing the DP chemistry. The calibration coefficients in the HSMM were then used to predict the cooling performance of the DP coils for a given gauge as seen in Figure 6. Figure 6 depicts the simulated post deformation cooling profile of this product, its estimated CCT curve, and the location of the pyrometers in LES HSM. The predicted cooling profile was compared to the actual measured temperatures obtained from the HSM’s pyrometers after each trial.

It was observed that the predicted values were within 30°C from the measured temperature traces, as seen in Figure 7. Also the statistical summary in Table 2 shows that the
highest absolute and percentage error were found with the coiling temperature. This can be contributed to the limited calibration data used in this regime (<150°C). Overall, the HSMM played an integral part in predicting the overall cooling profile of this product. This in turn reduced the number of mill trials needed since multiple ROT cooling configurations were employed within the same coil for different interruption time, which resulted in a variety of mechanical properties.

Figure 5: Cooling capability curves for HR DP product development trials
Figure 6: HSMM process simulations for the development of HR DP at Lake Erie Steel GP Inc.

Figure 7: Temperature comparison of HSMM predictions versus measured temperatures
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Avg. Absolute Error</th>
<th>Avg. Percent Error</th>
</tr>
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<tbody>
<tr>
<td>Finishing Temperature (FT)</td>
<td>19.2</td>
<td>2.46%</td>
</tr>
<tr>
<td>Interrupted Temperature (IT)</td>
<td>11.1</td>
<td>1.62%</td>
</tr>
<tr>
<td>Coiling Temperature (CT)</td>
<td>19.4</td>
<td>21.9%</td>
</tr>
</tbody>
</table>

Table 2: Statistical analysis of predicted versus measured temperatures

**Conclusion**

By using the INTEG Hot Strip Mill Model, Lake Erie Steel was able to simulate the production of hot rolled dual phase steel and effectively develop an initial rolling mill schedule, including the spray bank set-up for the run out table. The HSMM became an essential part of the development process due to its effective temperature prediction in an unknown mill temperature regime. The model successfully reduced the number of trials needed, which reduced the cost of mill time.

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List of Symbols

q \quad \text{Heat flux (W/m}^2\text{)}
F \quad \text{Liquid solid contact area fraction}
\text{m}_{lp} \quad \text{Macrolayer evaporation parameter}
\text{i}_{fg} \quad \text{Latent heat of vaporization (J/kg)}
A_{vw} \quad \text{Area in the macrolayer occupied by vapor}
T_{sat} \quad \text{Superheat, difference between the strip temperature and saturation}
\quad \text{temperature (°C)}
T_{sub} \quad \text{Subcooling, difference between the saturation temperature and actual}
\quad \text{water temperature (°C)}
\text{u} \quad \text{Velocity (m/s)}

Subscripts
TB \quad \text{Transition boiling}
\text{me} \quad \text{Macrolayer Evaporation}
\text{film} \quad \text{Film boiling}
g \quad \text{Vapour}
j \quad \text{Jet at impingement}
\text{nucl} \quad \text{Nucleate boiling}
\text{rad} \quad \text{Radiation}
sat \quad \text{Saturation}
References