idRHa+ProMod – Rail Hardening Control System

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Abstract. idRHa+ProMod is the process control system developed by Primetals Technologies to foresee the thermo-mechanical evolution and micro-structural composition of rail steels subjected to slack quenching into idRHa+ Rail Hardening equipments in a simulation environment. This tool can be used both off-line or in-line, giving the user the chance to test and study the best cooling strategies or letting the automatic control system free to adjust the proper cooling recipe. Optimization criteria have been tailored in order to determine the best cooling conditions according to the metallurgical requirements imposed by the main rail standards and also taking into account the elastoplastic bending phenomena occurring during all stages of the head hardening process. The computational core of idRHa+ProMod is a thermal finite element procedure coupled with special algorithms developed to work out the main thermo-physical properties of steel, to predict the non-isothermal austenite decomposition into all the relevant phases and subsequently to evaluate the amount of latent heat of transformation released, the compound thermal expansion coefficient and the amount of plastic deformation in the material. Air mist and air blades boundary conditions have been carefully investigated by means of pilot plant tests aimed to study the jet impingement on rail surfaces and the cooling efficiency at all working conditions. Heat transfer coefficients have been further checked and adjusted directly on field during commissioning. idRHa+ is a trademark of Primetals Technologies Italy Srl

1. Introduction
Rail market is increasingly asking for Premium rails, characterized by improved mechanical properties required to extend the useful lifecycle of high-speed and heavy-traffic railways. The answer of Primetals Technologies to the market call is idRHa+® an innovative and flexible rail hardening system, whose first application was installed at Baogang Iron and Steel plant in Baotou, China.

The system is able to in-line process both pearlitic and bainitic rails, with symmetric and asymmetric profiles, with a process velocity from 0.4 to 0.9 m/s and an inlet temperature range, from 700 to 850 °C. Depending on the requirements, several different cooling paths are to be followed to achieve the best metallurgical microstructure which requires a wide cooling regulation flexibility. This is made possible by special air-mist nozzles, which can modulate different water droplet sizes and velocities, as well as by high efficiency air blades which can decrease temperature in a very smooth way and complete the cooling process.

In order to satisfy market and producers’ needs, Primetals Technologies has developed the software idRHa+ProMod which, basically, simulates the in-line rail hardening process. The software is a
thermo-metallurgical model based on a 2D finite element simulator coupled with a routine which models the austenite decomposition into final product phases, and the subsequent release of latent heat occurring during the phase change. The software can work both off-line or in-line. The off-line mode allows the user to test different cooling strategies and to optimize all the process parameters. The in-line mode calculates the sensitivity of the system, compares the calculated results with the in-line pyrometric readings and automatically adjusts the pressure settings whether the temperature targets were not achieved due to changes in the nozzles behavior, due to wear or cloggings.

2. idRHA+ plant configuration with idRHa+ ProMod
Due to its modular design, idRHa+ProMod is very flexible and can be easily applied to any kind of plant configuration, having the possibility to input all the following components:

- Induction heating furnace units, position and length of each one.
- Plant sections, defined as the idRHa+ portions between two consecutive pyrometers and comprising some cooling modules.
- Control groups (CG), defined as ensembles of cooling modules sharing the same air and water pressure setting
- Cooling modules, both air mist or air blade ones
- Nozzles collectors, corresponding to rows of equal spaced or unequal spaced nozzles, with a proper orientation in space

Upper and lateral cooling section positions determine the way the rail head is impacted by the spray. In order to have a good spray coverage, idRHa+ProMod furnishes a view of the surfaces directly impacted by the jet (figure 1). This feature can be useful to decide a priori the upper collector height and then to optimize the jet impingement according to the simulated thermal paths.

![Figure 1. Spray impingement](image)

3. Thermal model
The Fourier heat conduction equation has been integrated by a 2D finite element approach in order to achieve a very fast and accurate thermal model. The method permits to correctly represent every different rail shape, also making the application of the boundary conditions easier and accurate. The weak formulation of the differential problem was used.

4 nodes linear isoparametric elements with full integration [1] have been chosen in order to use the minimum number of elements (figure 2) keeping a very good representation of internal temperature gradients, particularly under the rail head surface.

The finite element algorithm has been implemented in ANSI C so as to achieve the maximum performance, particularly useful for in-line calculation purposes.
4. Phase change model and thermo-mechanical material properties

For each rail material, the modeling of the metallurgical transformations by idRHa+ProMod requires the insertion of the proper Isothermal Transformation (IT) diagram. Nucleation and growth processes of diffusive, together with displacive transformations have been modelled (figure 3) according to the Scheil's Additivity Rule and the Johnson-Mehl-Avrami-Kolmogorov model (figure 4), and the amount of product phase can be evaluated as follows [2]:

\[ F_i(T) = 1.0 - \exp \left[ -a(T) \cdot t(T)n^{(T)} \right] \]

where \( F_i \) is the volume fraction of the product phase \( i \), \( t \) is the time elapsed since the transformation beginning, i.e. after the nucleation process, \( a \) and \( n \) are material parameters dependent on the isothermal temperature and the forming phase. The diffusional coefficient \( a \) and the transformation exponent \( n \) can be evaluated by the IT diagram of the considered material [3].
Figure 3. Rail internal field of temperature (top) and phase transformation (bottom) for the first two cooling sectors

Figure 4. Scheil's additivity rule (from TTT to CCT)
The latent heat due to solid phase transformations has been taken into account and included into the energy balance equation, using the following heat generation rate form:

\[ u_{\text{gen}} = \sum_i \Delta H_{i,j} \frac{\Delta F_{i,j}}{\Delta t_j} \]

where \( \Delta H_{i,j} \) is the heat of transformation of the phase \( i \) formed during the time step \( j \), at the temperature \( T_j \); \( \Delta F_{i,j} \) is the volume fraction of the transformed \( i \) phase, relatively to the same time step, and \( \Delta t_{i,j} \) is duration of the time step \( j \).

The amount of latent heat released during transformation from austenite to pearlite, bainite and martensite has been measured by calorimetric tests on several rail samples of different steel grades. Tests have been conducted at the Metallurgy laboratories of Politecnico di Milano (Polytechnic University of Milan).

On the one hand, in order to optimize the solution routine, saving computational time, the thermal and phase change models have been decoupled, and a different time step, for each model, has been adopted. On the other hand, in order to reduce computational costs, a relatively larger time step has been used for the microstructural model, without any appreciable accuracy decreasing.

Temperature dependent material properties, taken from literature formulas \([4]\) or tables \([5]\), have been evaluated and updated at quite large time steps, so as to avoid frequent time consuming FEM matrix assemblies operations. Density, thermal conductivity, specific heat, yield stress and Young modulus have been estimated for each metallurgical phase available and have been further mixed together at each element integration point by means of a rule of mixture \([4]\), taking into account the volume fractions of the formed phases.

5. Bending Estimation

Rail inflection deserves a particular attention, since a proper evaluation of the bending radius avoids clearance problems with the rail entering the cooling system. Rail curvature is affected by two opposite physical effects: the thermal contraction of metal due to the fast and inhomogeneous temperature reduction and the volume expansion due to the metallurgical transformations. A tradeoff is not easy to be evaluated a priori, because it strongly depends on the rail inlet conditions (steel grade, rail shape, temperature and phase content, in particular the amount of transformations already started on foot). Curvature evolution does not linearly depend on the cooling intensity, because the internal rail section stress and strain are affected by non-linear temperature dependent transformation rates and unfortunately also by the previous sectors cooling policy.

The internal stress and strain state, and consequently the integrated elastic-plastic bending curvature are calculated by the software along the length of the idRHa+ system (figure 5). A 2D approximation has been adopted and so rail section is supposed to remain plane during inflection. Rail section curvature (figure 6) and longitudinal contraction have been calculated by a fast iterative solver, making also considerations about the self weight contribution and running iterations till the achievement of the proper equilibrium of section forces and moments.
Figure 5. Evolution of rail internal field of plastic strain (top) and elastic stress (bottom) during heat treatment

Figure 6. Curvature evolution (bottom curve) and average head and foot transformation (top curves)

The maximum curvature limit can be chosen by the user or, alternatively, default values, based on geometrical equipment limitations, can be kept. Curvature could be interpreted as the rotation angle (radians) formed by a 1 m long rail, as shown in figure 6. Automatically, idRHa+ProMod can simulate several scenarios in order to find the best pressure setting, taking into consideration both the optimal metallurgical structure and risks associated with excessive bending.
6. HTC measurement and modeling

Laboratory trials conducted by CSM (Centro Sviluppo Materiali) in Italy at the pilot plant in Dalmine (Italy) permitted the evaluation of the HTC (heat transfer coefficient) of both mist nozzles and air blades.

Cooling tests were performed on real rail specimens and on an austenitic plate, equipped with several thermocouples. The samples were heated up to 900 °C and then cooled down to ambient temperature using different nozzles pressures. All trials were modeled by a commercial finite element software and related HTCs were obtained by inverse modeling techniques (figure 7).

Air mist jet properties like water specific flows, droplet velocities and Sauter Mean Diameter \( (D_{32}) \) were measured (figure 8) and a comprehensive HTC correlation as function of air and water pressures was found (figure 9), based on the following literature equation [6]:

\[
HTC \propto D_{32}^k \cdot v_{imp}^l \cdot N^m
\]

where \( v_{imp} \) and \( N \) are the impinging velocity of droplet and the number density of droplets, respectively.

![Figure 7. FEM model for inverse modeling (Celsius scale)](image)

![Figure 8. Sauter Mean Diameter measures](image)
Similarly, pressures and velocities of air blade jets were correlated to the experimental HTC values.

### 7. Induction heating modeling

Being the idRHa+ system equipped with induction heating furnaces, so as to homogenize the temperature along the rail length, a simplified and fast electromagnetic simulation model was tailored on the base of preliminary FEM analysis. This analysis was carried out by the induction heating system supplier with the use of the commercial finite element software ANSYS. Thus, it was possible to find geometrical correlations between the full FEM analysis and the well-known electromagnetic penetration depth formula,

\[
\delta = \sqrt{\frac{\rho}{\pi \mu f}}
\]

\[
\begin{align*}
\rho : & \quad \text{resistivity} \quad [\Omega \cdot m] \\
\mu : & \quad \text{magnetical permeability} \quad [H/m] \quad (\mu = \mu_0 \mu_r) \\
\quad f : & \quad \text{frequency} \quad [Hz]
\end{align*}
\]

which is the solution of Maxwell’s equations for semi-infinite bodies subjected to a uniform magnetic field but it’s also suitable for cylindrical bodies with diameter bigger than \(\delta\). The specific heat produced inside the whole rail section was calculated at each element integration point and then summed up to the \(u_{\text{gen}}\) term of the thermal model (figure 10). Results of the simplified electromagnetic model were in agreement with the full ANSYS FEM analysis.
8. Industrial application

According to the temperatures measured by the in-line pyrometers positioned at the inlet of the cooling system, idRHa+ProMod can estimate the rail incoming thermal profile. Once the thermal map is established, idRHa+ProMod performs calculations at different pressure settings for each control group, then simulates the corresponding thermal path and finally, after a few iterations, finds out the optimized one. Cooling path optimization is based on the following criteria:

- Dropping down temperature as fast as possible at the early stages of the heat treatment. This choice permits to control metallurgical transformations as long as possible inside the idRHa+ system and to obtain hard structures deep inside the rail surface.
- Increasing the surface temperature over the pearlite limit (PL) so as to avoid bainite start.
- Keeping the surface temperatures very close to a predefined target temperature until microstructural transformations have finished.
- Adjusting the pressures so as to keep the rail straight.

All the thermal profiles, cooling paths and calculation results are available for display on the user interface (figure 11).
Currently, idRHa+ProMod rail hardening control software is used by Baogang Iron and Steel in Baotou (China). This thermo-metallurgical software was first employed during the idRHa+ hot commissioning in April 2014, giving valuable information about the possible cooling strategies and suggesting the applicable pressure settings for different rail shapes, materials, temperatures and process velocities.

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