Mathematical Simulation and Controlled Cooling in an EDC Conveyor of a Wire Rod Rolling Mill

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The aim of this work was to build up a model, working on a PC, able to simulate the controlled cooling of wire rods in an EDC conveyor. The effect of the cooling pattern on the temperature profile and the austenite microstructural evolution during hot rolling have been studied.

This computing system will provide a high flexibility for simulating different operational conditions and for forecasting the thermal and microstructure evolution during the cooling after hot rolling, including the prediction of microstructural final properties, in the EDC conveyor of the SIDENOR wire rod rolling mill in Vitoria.

The use of this integrated model enables calculation of the temperature distribution through the section and along the width of the loop, and allows a systematic study of the parameters influencing the cooling behaviour. Besides, the effects of different parameters and their complex correlation can be studied.

KEY WORDS: wire rod; controlled cooling; mathematical modelling; EDC conveyor; cooling patterns.

1. Introduction

A mathematical model able to predict the cooling rate of wire rods in an EDC conveyor, taking into account operation parameters, cooling conditions and other inherent process parameters, has been developed. This model in combination with an austenitic and microstructural model will enable to produce important quality and productivity benefits.

This work has been specifically designed for the EDC system of the SIDENOR wire rod rolling mill in Vitoria. In this EDC system, several controlled cooling processes are possible to achieve depending on the steel grade to be rolled and on the requested properties of the customer. It is to say:

– Air-cooling,
– Retarded cooling (covers),
– Cooling in boiling water,
– Direct quenching after rolling.

Just before the laying head the rod travels through cooling devices that provide control over the rod temperature, affecting austenitic grain size prior to controlled cooling (Fig. 1).

In all cases complex cooling patterns must be taken into account due to differences between centre and edge of the loop in the conveyor. In this study, it will be presented a brief theoretical study in order to get a better understanding of this intrinsic heterogeneity of the EDC cooling.

2. Simulation Tool

A simulation tool able to predict the thermal history, and metallurgical evolutions of the wire rod during its cooling on the conveyor as well as its final microstructure and mechanical properties will allow improved definition of industrial cooling presets with respect to the quality of the product.

Most metallurgical operations involve thermal phenomena whose kinetics exert a preponderant influence on the quality of the final product; but it is also known there is a strong influence of austenite grain size on transformation behaviour and on wire rod final characteristics. Because of this, in the present study, thermal phenomena dependent on heat transfer between the metal and the environment, and microstructural evolution, in terms of austenitic grain size after rolling, will be determined.

The flow chart shown in Fig. 2 describes the integrated mathematical model, its sub-models and links.

3. Thermal Sub-model

Heat flow in the long rods processed on the EDC is mainly through the radial direction, governed by following unsteady heat conduction equation:

![Fig. 1. Schematic diagram of a rod mill EDC area.](source)
The boundary conditions for the solution of Eq. (1) are the following:

\[
-\lambda \frac{\partial T}{\partial r} \bigg|_{r=0} = 0 \quad (2)
\]

\[
-\lambda \frac{\partial T}{\partial r} \bigg|_{r=R} = h(T - T_a) \quad (3)
\]

For the initial condition, the rod is assumed to be isothermal at temperature \(T_0\):

\[
T(0) = T_0 \quad (4)
\]

where \(\lambda\), \(C_p\) and \(\rho\) are thermal conductivity, heat capacity and steel density, and \(h\) is the overall heat-transfer coefficient that usually involves forced convection and radiation. \(\lambda\) and \(C_p\) are temperature-dependent functions obtained from the literature \(^{11}\) that have been adjusted to simple equations (Tables 1 and 2); steel density \((\rho)\) is assumed constant over the temperature range of interest.

### 3.1. Air Cooling

In the EDC air cooling process there is no forced convection, and the effects of the natural convection are extremely small in comparison with losses due to radiation, so they can be neglected. Radiation heat losses from an air-cooling process is strongly dependent on temperature and is governed by the Stefan–Boltzmann law, according to the following equation:

\[
\alpha_{\text{Radiation}} = F_{ij} \sigma \left( \frac{T_{\text{surf}}^4 - T_{\text{env}}^4}{T_{\text{surf}}^4 - T_{\text{ext}}^4} \right) \quad (5)
\]

where \(T_{\text{surf}}\) is the surface temperature of the rod, \(T_{\text{env}}\) is the surroundings temperature (covers temperature in case of retarded cooling) and \(T_{\text{ext}}\) is the external temperature (air temperature), in K. \(F_{ij}\) is a radiation factor.

This is a practical but extremely global representation of the heat transport mechanism, since all the influences have to be integrated in a single factor \(F_{ij}\), which accounts for the emissivity, relative geometries of the cooling body and its surrounding. In the EDC system the value for \(F_{ij}\) is essentially variable along the width of the conveyor depending on the overlapping pattern of the steel rod loops, it is to say, on mass density.

It is known that the lower mass density \((m)\) higher equivalent exchange surface and higher cooling rate. The variation of \(m\), along the width of a layer of non-concentric loops laid on a conveyor, has been calculated by assimilating the loops of wire circles and applying a differential calculus law. The parameters taken into account have been those affecting mass density: diameter and loop density \((N)\). \(N\) is a function of the conveyor \((v)\) and rolling \((V)\) speeds and of the mean loop diameter \((D)\), we have adopted \(D=1\) 150 mm.

### Table 1. Thermal conductivity \([\text{J} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{°C}^{-1}]\) of different steel grades.

| Steel range     | Thermal conductivity \((\lambda)\) | Observation |
|-----------------|-----------------------------------|-------------|
| CARBON STEEL    | 0.481 + 0.2(T/1000) + 0.794 exp(-0.0261(T-768)) | T ≥ 768 °C  |
|                 | 0.481 + 0.2(T/1000) + 0.81 exp(-0.0097(768-T)) | T < 768 °C  |
| ALLOY STEEL     | 1.96x10^4 T + 0.407 -4.91x10^4 T + 4.62 0.00997x5.363 5.78x10^4 T + 0.45 | T ≥ 825 °C  |
|                 | 19.13 + 0.0089 T | 675 ≤ T ≤ 825 °C |
|                 | 19.13 + 0.0089 T | 625 ≤ T ≤ 675 °C |
|                 | 19.13 + 0.0089 T | T ≤ 625 °C   |
| BEARING STEEL   | 5x10^4 T + 0.61 -0.288T + 22.969 0.025T-16.395 5.5x10^4 T + 0.445 | T ≥ 775 °C  |
|                 | 725 ≤ T ≤ 775 °C | 675 ≤ T ≤ 725 °C |
|                 | 725 ≤ T ≤ 775 °C | T < 675 °C   |
| STAINLESS STEEL | 7.5x10^4 T + 0.336 | T in °C     |

### Table 2. Heat Capacity \([\text{kJ} \cdot \text{kg}^{-1} \cdot \text{°C}^{-1}]\) of different steel grades.

| Steel range     | Heat capacity \((C_p)\) | Observation |
|-----------------|------------------------|-------------|
| CARBON STEEL    | 0.481 + 0.2(T/1000) + 0.794 exp(-0.0261(T-768)) | T ≥ 768 °C  |
|                 | 0.481 + 0.2(T/1000) + 0.81 exp(-0.0097(768-T)) | T < 768 °C  |
| ALLOY STEEL     | 1.96x10^4 T + 0.407 -4.91x10^4 T + 4.62 0.00997x5.363 5.78x10^4 T + 0.45 | T ≥ 825 °C  |
|                 | 19.13 + 0.0089 T | 675 ≤ T ≤ 825 °C |
|                 | 19.13 + 0.0089 T | 625 ≤ T ≤ 675 °C |
|                 | 19.13 + 0.0089 T | T ≤ 625 °C   |
| BEARING STEEL   | 5x10^4 T + 0.61 -0.288T + 22.969 0.025T-16.395 5.5x10^4 T + 0.445 | T ≥ 775 °C  |
|                 | 725 ≤ T ≤ 775 °C | 675 ≤ T ≤ 725 °C |
|                 | 725 ≤ T ≤ 775 °C | T < 675 °C   |
| STAINLESS STEEL | 7.5x10^4 T + 0.336 | T in °C     |
It can be seen (Figs. 3 and 4) that the mass density varies in a large extend along the width of the loop. In Fig. 3 mass density has been obtained as a function of loop density (rod diameter as constant). In Fig. 4 mass density has been calculated as a function of diameter (loop density as constant).

The mass density, for a determined diameter, can be varied modifying the conveyor speed. In Figs. 5 and 6, finally, it has been obtained the influence of diameter and conveyor speed in mass density at the centre and edge of the loop.

For this calculations, the diameter/finishing rolling speed relationship in the wire rod mill of SIDENOR has been adopted.

The value of $F_{ij}$ could be calculated from these geometrical considerations but this task is extremely complicated. For that reason an experimental approach is needed.

3.1.1. Numerical Solution

Solution of differential Eq. (1) is not possible analytically, due to the variation of $C_p$, $\lambda$, and $\alpha$ with temperature. Thus, an implicit finite-difference technique was applied by discretizing time and rod section.

To back calculate the heat-transfer coefficient from the temperature at the surface of the product it has been solved the inverse problem of heat conduction; this method comprises two stages, firstly, an experimental determination and secondly, a numerical calculation.

The experimental determination of time-temperature curve in the EDC of SIDENOR in Vitoria was performed by carrying out in-plant measurements by a LAND infrared thermographer with an emissivity set at 0.8. The thermographer was previously calibrated by the supplier company.

The thermographer allows obtaining an image of the thermal state of the whole of the loop (Fig. 7). A battery of measurements was performed, at different points along the conveyor (Fig. 8), under all possible operational conditions.

A trial and error scheme has been used to solve the inverse problem of heat conduction, whereby the heat-transfer coefficient is initially guessed, then finite-difference equations are employed to solve the through section thermal profile, and the predicted temperature on the surface is compared with measured values.

From the calculated heat-transfer coefficients it has been derived the radiation factor, $F_{ij}$, of Eq. (5). This factor has been converted into an expression as a function of those parameters affecting the geometry of the overlapping rods and mass density, it is to say, loop density and diameter. An optimisation of the square $R$ regression adjustment parameter has been carried out in SIDENOR I+D by non-linear re-
gression analysis, obtaining the following expression to calculate \( F_{ij} \) at the centre and edge of the loop, in both cases: air-cooling and retarded cooling:

\[
F_{ij} = a_i \left( \frac{12}{D} \right)^{\alpha_i} N^{-\beta_i} T^{\gamma_i} \quad \ldots \ldots \ldots \ldots (7)
\]

where \( N \) is the loop density (loops/m), \( D \) is the diameter of the rod in mm, \( T \) the surface temperature of the rod in K and \( a_i, \beta_i, \gamma_i \) are constants depending on the position along the loop (centre/edge) and on the cooling process (air-cooling/retarded-cooling).

The thermal prediction of this sub-model has been validated by comparing with experimental in-plant measurements showing excellent agreement with measured values. In Fig. 9 is presented an example of this accurately response.

The calculated values of \( F_{ij} \) together with the analytic formulation of the heat transfer coefficients presented above constitute a complete description of still air cooling on an EDC conveyor.

### 3.2. Boiling Water Cooling

In case of a cooling process by immersion into a liquid, boiling or cold water, the heat transfer coefficient must take into account film boiling and nucleate boiling stages, the radiation is not considered.

For temperatures of the water near the boiling point, the critical rod temperature at which nucleate stage starts is lower than the temperatures at which perlitectic transformation is completed. So the cooling process when cooling in boiling water in the EDC water tank can be assumed to be a matter of film boiling stage. According to several researchers’ works\(^4\) the heat transfer coefficient in film boiling can be calculated by this expression:

\[
\alpha_{Total} = 540 \cdot \Phi \cdot d^{-0.25} \quad \left[ \frac{W}{m^2 \cdot K} \right] \quad \ldots \ldots \ldots \ldots (8)
\]

where \( d \) is the rod diameter [mm], and \( \Phi \) is a coefficient taking into account the effect of water temperature.

In Fig. 10 is presented the value of \( \Phi \) as a function of water temperature, calculated by in-plant measurement in the EDC of SIDENOR by infrared thermography and by thermocouples in the water.

Calculated values of heat-transfer coefficient along the EDC conveyor in Vitoria, by applying similar modelling procedure as explained in previous paragraphs, are shown in Fig. 11. It is to be remarked the variations of this coefficient in the part concerning boiling water cooling, and in the last part with no covers.
4. Austenitic Sub-model

The state of the austenite just before controlled cooling in the EDC conveyor, is dependent on its complete previous forming and temperature history: temperature, strain and strain rate, and on the composition of the material.

Many authors have performed works in the field of modelling microstructural evolution during hot rolling of wire rods. The expressions used in this work are derived from those given by Maccagno, Jonas and Hodgson.\textsuperscript{5)} The austenitic grain size predicted by these expressions are in good agreement with experimental grain size obtained by freezing the material in different points of the wire rod rolling mill in Vitoria. These formulae are described below.

During hot rolling, the first metallurgical phenomenon that must be accounted for is dynamic recrystallisation, since it occurs during the course of deformation. Dynamic recrystallisation initiates at a critical strain, $\varepsilon_c$, that is calculated from the grain size at the start of the pass $d_0$, the strain rate and the absolute temperature $T$ (K):

$$
\varepsilon_c = 5.6 \times 10^{-4} d_o^{0.3} Z^{0.17}
$$

where $Z = \dot{\varepsilon} \exp(300,000/8.31 T)$ is the Zener–Hollomon parameter.

The softening mechanism after each pass will depend on whether the critical strain required to initiate dynamic recrystallisation is reached or not. Conventional static recrystallisation (SRX) will occur if the pass strain is less than the critical strain, otherwise the softening will be produce by metadynamic recrystallisation.

The kinetics of recrystallisation in hot working can be described by the Avrami equation:

$$
X = 1 - \exp \left[ -0.693 \left( \frac{t}{t_{0.5}} \right)^q \right] \quad \text{(10)}
$$

where $X$ is the volume fraction recrystallised after time $t$. The exponent $q$ and the time for 50\% softening, $t_{0.5}$, depend on whether the softening is by static recrystallisation or metadynamic recrystallisation:

- if $\varepsilon < \varepsilon_c$, then
  $$
  q = 1
  $$
  SRX:
  $$
  t_{0.5} = 2.3 \times 10^{-15} \dot{\varepsilon}^{-2.5} \exp \left( \frac{230,000}{8.31 T} \right) \quad \text{(11)}
  $$

- if $\varepsilon > \varepsilon_c$, then
  $$
  q = 1.5
  $$
  MRX:
  $$
  t_{0.5} = 1.1 Z^{-0.8} \exp \left( \frac{230,000}{8.31 T} \right) \quad \text{(12)}
  $$

The grain size ($\mu$m) produced by complete recrystallisation, if the softening is by SRX is described by:

$$
\frac{d_{SRX}}{d_0} = 343 \dot{\varepsilon}^{-0.8} d_o^{0.4} \exp \left( -45,000 \left( \frac{8.31 T}{T_{SRX}} \right) \right) \quad \text{(13)}
$$

Similarly, if it is described by MRX:

$$
\frac{d_{MRX}}{d_0} = 2.6 \times 10^4 Z^{0.23}
$$

When recrystallisation is complete, further growth may take place even in the relative short times available between passes ($t_{ip}$) in hot rolling. The grain coarsening is well described with second order equations for times shorter than 1 s, and with seventh order equations starting from that time:

For SRX:

- $t < 1$ s,
  $$
  d^2 = d_{SRX}^2 + 4 \cdot 10^7 (t_{ip} - 4.32 t_{0.5}) \exp \left( -113,000 \left( \frac{8.31 T}{T_{SRX}} \right) \right) \quad \text{(15)}
  $$

- $t > 1$ s,
  $$
  d^7 = d_{SRX}^2 + 1.5 \cdot 10^7 (t_{ip} - 4.32 t_{0.5}) \exp \left( -400,000 \left( \frac{8.31 T}{T_{SRX}} \right) \right) \quad \text{(16)}
  $$

For MRX:

- $t < 1$ s,
  $$
  d^2 = d_{MRX}^2 + 2.6 \times 10^7 (t_{ip} - 2.65 t_{0.5}) \exp \left( -113,000 \left( \frac{8.31 T}{T_{SRX}} \right) \right) \quad \text{(17)}
  $$

- $t > 1$ s,
These formulae describe the grain size evolution during rod rolling but implying that the microstructural events occur under isothermal conditions. Interpass times are short enough to be applied an average temperature without important deviations, but this assumption is clearly inappropriate for subsequent water sprays cooling process into the water boxes placed between the finishing block and the laying head prior to the EDC conveyor. As far as the aim of this sub-model is to obtain the austenitic grain size at the entrance of the EDC conveyor, above equations must be suitably transformed to allow their use inside these cooling devices.

To enable these isothermally determined equations to describe the behaviour under non-isothermal conditions, the use of ‘temperature compensated time’ \((w)\) is needed. This is defined as:

\[
 w = \sum_i \delta t_i \exp \left( -\frac{Q}{RT_i} \right) 
\]

where \(\delta t_i\) is the finite difference time step at which the temperature was \(T_i\).

Replacing the ‘temperature compensated time’ \((w)\) in those equations referring grain coarsening (Eqs. (15)–(18)), it will be obtained a modified grain growth equation as presented, in a general manner, below. This equation will enable to assess the austenitic grain coarsening under non-isothermal conditions:

\[
d^n = d_{\text{MRX}}^n + A \sum_i \delta t_i \exp \left( -\frac{Q}{RT_i} \right) 
\]

To estimate \(T_i\) and \(\delta t_i\) it is necessary to predict the rod cooling behaviour inside water boxes. Between the finishing block and the laying head, three water boxes are spaced: the first two boxes, approximately 6 m long contains 9 cooling nozzles, the third water box, approximately 4 m long, contains 6 nozzles and is usually employed as a second equalisation zone.

The modelling procedure is similar to that already explained in previous paragraphs. In this case two different heat-transfer coefficients have to be considered: radiation and strong convection. The details for calculating these heat-transfer coefficients have been sufficiently discussed by several authors. In this case, the strong convection heat-transfer coefficient has been taken from the considerations of Morales et al.\footnote{Figures 12 and 13 show the thermal evolution inside the cooling devices predicted by the model and the through section thermal gradient at the exit of them. The results obtained by the application of above scheme are presented (Fig. 14) in the case of rolling a rod diameter 13 mm. The model is also able to predict the variation of the mean austenite grain size along the stock diameter due to the thermal gradient. The agreement is very good despite the fact it is been ignored the through-thickness thermal gradient produced in the roll bite, and the equations are

\[
d^7 = d_{\text{MRX}}^7 + 8.2 \cdot 10^{25}(t_p - 2.65t_{0.5}) \exp \left( \frac{-400 \, 000}{8.317} \right) 
\]

Fig. 12. Thermal profile inside the cooling devices. Rod diameter = 13 mm.

Fig. 13. Thermal gradient along the rod diameter at the exit of the cooling devices. Rod diameter = 13 mm.

Fig. 14. Austenitic grain size evolution during hot rolling. Rod diameter = 13 mm.

Fig. 15. Comparison of the predicted austenitic grain sizes by the model with those measured at the entering of the conveyor.
based on the assumption of homogeneous strain. Figure 15 shows the comparison of measured and predicted mean grain sizes in a 13 mm diameter rod (41Cr4 steel grade).

5. Validation

With the austenitic grain size and cooling rate values calculated with the above two sub-models, hardness, transformation temperature and percentage of microstructures can be derived from a CCT diagram prediction model, composed by a library of CCT and dilatometric studies of those steels rolled and controlled cooled in the EDC of SIDENOR. Semilogaritmic interpolation allows obtaining these parameter from every austenitic grain size and cooling rate.

These three sub-models have been integrated in an user friendly simulation tool, for use on PC under Microsoft Windows that provides conviviality to manipulate the data and to handle the results of simulations.

The agreement between the predicted and measured values demonstrates the capability of the model to predict microstructures and hardness of continuously cooled special steels rod for industrial conditions. Two examples of this good agreement are shown in Tables 3 and 4.

6. Conclusions

An integrated model has been developed able to describe the microstructural evolution of steels and cooling patterns in the EDC conveyor of SIDENOR wire rod rolling mill in Vitoria, including the prediction of microstructural final properties.

This model enables to quantify the effect of diameter, steel, laying head temperature, and different cooling practices on microstructure and thermal profile along the EDC conveyor.

Thermal gradients along the diameter of the rod and along the width of the loop have been considered. The application of this global model has already produced many benefits in the SIDENOR process:

− Minimisation of industrial trials.
− Enhancement current product properties by an optimisation of the cooling practices.
− Assessment the feasibility of manufacturing new steel grades in the EDC.

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