Modelling of Microstructure and Heat Transfer during Controlled Cooling of Low Carbon Wire Rod

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The microstructure of TMT (Thermo-Mechanically-Treated) rebars consists of four phases, tempered martensite, bainite, ferrite and pearlite. These four phases are non-homogeneously distributed across the cross section of the wire rod which gives rise to a complex hardness distribution. A coupled heat transfer and phase transformation model has been developed at the R & D Division of Tata Steel that can predict the temperature profile and the fraction of various phases in this type of wire rods efficiently. A fully implicit finite difference scheme has been used for solving the heat transfer equation in cylindrical coordinates; the recalescence due to phase transformation has been taken into consideration that makes the model suitable for use in any industrial application. A model has also been developed based on the volume fraction and strength of the individual phases to predict the hardness at different sections of the wire rod. The predicted hardness distribution has been found to agree well with the micro hardness measurements at various points across the section of the wire rod.

KEY WORDS: microstructure; modelling; heat transfer; low carbon steel; hardness profile.

1. Introduction

In the Wire Rod Mill (WRM), billets of appropriate dimension are heated in the reheating furnace to the austenite region and passed through subsequent reductions in the rolling strands to get the wire rod of the desired diameter. After the rolling, the wire rod is passed through water boxes where it is quenched using high pressure water jet. The cooled rod thereafter approaches a conveyor where it is cooled by natural convection and radiation to the atmosphere or by passing forced air from below. The cooling rate in this region can be controlled by varying the opening of the blowers that blows the air and also by covering selected regions of the conveyor with hoods. The temperature of the outer region of the wire rod goes below the Ms temperature as the rod is quenched in the water boxes and a uniform martensite rim is formed. This is subsequently tempered by the heat flow from the core of the wire rod. Various regions inside the rod experience different cooling rates, and as a result, a gradient of microstructure evolves. A schematic temperature profile of the wire rod cooled in the water box is shown in Fig. 1. If the microstructure of the rod is observed it is found that at the center there is a mixture of ferrite and pearlite (with a very little amount of bainite in some cases), the tempered martensite rim is there at the surface and in between these two regions there is a bainite rich area.

The strength and toughness of the TMT rebar depend on its rim thickness as well as on the distribution of various phases inside the wire rod. The rim thickness in the rebar is related to the rolling condition as well as to the material property (Ms temperature). Therefore, it is necessary to control the rolling parameters in such a way that a desired rim thickness is achieved along with the correct combination of microstructure across the section. The control of various cooling parameters, which governs the heat transfer and phase transformation mechanism inside the wire rod, requires a coupled mathematical model of phase transformation and heat transfer. A coupled model would be particularly helpful to generate an accurate temperature profile of the wire rod as the heat generation due to phase transformation affects the temperature profile of the wire rod considerably. Agarwal and Brimacombe have successfully developed a model for predicting heat transfer and phase transformation in high carbon wire rods. They used the Scheil’s additivity principle and TTT diagrams from Atlases for evaluating the constants for Avrami equation. Campbell et
al. used experimentally determined CCT diagrams to determine the transformation start time and temperature; they evaluated the constants of Avrami equation with the help of an empirical formula. Campbell et al. could determine successfully the temperature evolution and phase transformation kinetics in low-carbon wire rods.

The present work aimed at the development of a phase transformation and hardness prediction model that would be able to predict the amount of various phases across the diameter of the TMT wire rod along with the hardness profile. Since several different phase evolutions need to be tracked simultaneously, the model is non-trivial. As mentioned earlier the evolution of a gradient microstructure in the rod takes place because of the different cooling rate experienced at different radii (Fig. 1). This prediction of the kinetics of the phase transformation necessitates development of a coupled thermal model capable of predicting the temperature profile of the wire rod as it passes through the various cooling regime in the mill.

The model takes various rolling parameters and prior austenite grain size as the input and predicts the amount of different phases and temperature profile along the wire rod diameters; it also generates a through-thickness hardness profile which can be used for predicting the YS and UTS of the wire rod.

2. TMT Process Overview

The control of the cooling process in WRM is the key to achieving the mechanical and microstructural properties of many grades of wire rod rolled in the mill. A typical process flow diagram of WRM is shown in Fig. 2.

Billets are soaked at different temperatures in the furnace depending on the chemistry of the steel. Thereafter the billets are passed through various roughing and intermediate strands before the finishing mill, also known as No-Twist-Mill (NTM). In this region the rod undergoes metadynamic recrystallisation and thus the evolution of austenite grain size prior to the phase transformation gets affected. After passing through the NTM, the rods enter into the cooling region. The cooling region consists of several water boxes, inside which exist a number of cooling nozzles. The rod passes through these water boxes and can be cooled at different cooling rates depending primarily on the rolling speed, water pressure and the amount of water flow. The water boxes provide the necessary control over the rod temperature prior to continuous cooling and thus affect the prior austenite grain size. After the water-cooling region the rod is looped continuously into a coil and placed on a conveyor bed (known as the Stelmor conveyor or Stelmor bed), where a chain conveyor pulls it through the successive forced air cooling zones. The region where the coils fall on the cooling conveyor is known as the Laying Head area. The temperature of the wire rod at this region is regarded to be an important process variable for controlling the wire rod property and known as Laying Head Temperature (LHT). The cooling of wire rods on the conveyor is done with the help of forced air blown from below the conveyor. The air is blown with the help of a series of fans in zones; the cooling rate being controlled by the variation of the blower opening of the fans as well as by the variation of the speed of the conveyor. The rate of cooling of the rod can also be reduced drastically by covering the coils with the help of a hood, which is used for some special low carbon grades. Generally a higher cooling rate is employed in the case of high carbon grades and a slower cooling rate is used for low carbon grades.

3. Development of Models

3.1. Heat Transfer Model

The heat transfer model has been developed for the water box and the conveyor regions. Heat flow in an infinitely long steel rod moving at high speed and cooled uniformly from all sides is governed, after appropriate transformations, by the following transient heat conduction equation, which is valid for both the water box and the conveyor regions.

$$\frac{\partial}{\partial r} \left( k \frac{\partial T}{\partial r} \right) + \frac{k}{r} \frac{\partial T}{\partial r} + q_{TR} = \rho C_p \frac{\partial T}{\partial t} \hspace{1cm} (1)$$

where $k$ is the thermal conductivity, $\rho$ is the density and $C_p$ is the heat capacity of steel. This formulation assumes that the heat flow by temperature gradients in the direction of the motion of the rod is negligible compared to bulk motion in that direction—an assumption justifying the high rolling speed. $q_{TR}$ is the heat released due to the transformation of austenite to other phases (i.e. ferrite, pearlite, bainite or martensite) and $q_{TR}$ can be written as:

![Fig. 2. Layout of a typical wire rod mill.](image)
where, $\Delta X$ is fraction of the phase formed from austenite, $\Delta H$ is the generation of heat due to phase transformation per unit weight (kg).

The boundary condition at the rod surface and center are:

For $t > r = r_{0}$, $-k \frac{\partial T}{\partial r} = h_{W}(T_{S} - T_{A})$ \hspace{1cm} (3)

$t \geq 0$, $r = 0$, $\frac{\partial T}{\partial r} = 0$ \hspace{1cm} (4)

while the initial condition is:

$t = 0$, $0 \leq r \leq r_{0}$, $T = T_{\infty}$ \hspace{1cm} (5)

where $h_{W}$ represents the overall heat transfer coefficient and $T_{\infty}$ is the initial temperature of steel.

A fully-implicit finite difference scheme has been developed to solve Eq. (1). The model incorporates temperature dependent thermal conductivity and specific heat of various phases along with heat generation due to phase transformation. Although the WRM process employs forced air for cooling purpose on the conveyor and high pressure water jet in the water boxes, radiation from the rod surface also contributes substantially in removing the heat. As a result the overall heat transfer coefficient must be calculated taking both radiation and convection into consideration.

\[ h_{W} = h_{r} + h_{g} \] \hspace{1cm} (6)

The heat loss due to radiation from the surface of a steel rod can be expressed as:

\[ h_{r} = \sigma R(T_{S}^{4} - T_{A}^{4})/(T_{S} - T_{A}) \] \hspace{1cm} (7)

where $R$ is a radiation factor comprising the emissivity of steel and the relative geometry of the material. $\sigma$ and $\varepsilon$ are the Stephan–Boltzman constant and emissivity of rod respectively, $T_{S}$ and $T_{A}$ represents the surface temperature of rod and the atmosphere (in K) respectively.

The calculation of heat transfer coefficient at the various stages of cooling is a difficult task. During the cooling of the wire rods inside the water boxes, the heat transfer coefficient may change drastically depending upon whether the water jet impinges on the rod surface directly or the cooling is due to the carry over of the water on the surface of the rod. A very systematic study of the published literature on this subject has been done by Morales and coworkers,\(^3\) it has been found that for the present work the following expression for the heat transfer coefficient inside the water box is the most appropriate:

\[ h_{W} = AW^{2}(1 - 0.0075S_{w}) \] \hspace{1cm} (8)

where $A$ and $B$ are constants, $W$ is the water flow rate (L/min) and $S_{w}$ is the temperature of the water in degree centigrade.

Just after the impingement zone, there could be water carry over and the heat transfer mechanism in this zone belong to the unstable film boiling regime. According to this mechanism the heat transfer coefficient for convective heat transfer is given by:\(^4\):

\[ h_{c} = 0.62 \left[ \frac{H_{w} \rho g (\rho_{w} - \rho) k^{3}}{\mu(T_{w} - T_{\infty}) D} \right]^{1/4} \] \hspace{1cm} (9)

where $H_{w}$ is the effective heat of vapourisation of water, $k$ and $D$ are the thermal conductivity and the diameter of wire rod, $\mu$ and $\rho$ are the viscosity and density of steel and $\rho$ is the density of the water vapor, $T_{w}$ is the surface temperature of rod and $T_{\infty}$ is the saturation temperature of water.

Inside of the water boxes, where the rod comes in contact with the water directly, assumed to be the impingement zone and Eq. (8) have been employed to calculate the heat transfer coefficient. It has been assumed that water carry over takes place when the rod passes through the region in between two water boxes and also when it traverses the distance from the end of last water box to the pinch roll that guides the rod to fall on the laying head area.\(^5\) In this region Eq. (9) has been used.

Heat transfer coefficient for convective heat transfer depends on air velocity and rod diameter and these key factors must be controlled on the conveyor. Correlations for the convective heat transfer from cylindrical bodies are available in the literature. These correlations are empirical in nature and relate the Nusselt number (Nu) to Reynold's number (Re) and Prandtl (Pr) number.

One of such relationships is:

\[ Nu = C Re^{0.3} Pr^{0.25} \] \hspace{1cm} (10)

Where $C$, $x'$, $y'$ are constants and depend on the cooling medium. Based on this principle Isachenko et al.\(^5\) has derived this relationship for calculating the convective heat transfer coefficient.

\[ Nu = 0.5 Re^{0.5} Pr^{0.18} \left( \frac{Pr_{r}}{Pr_{t}} \right)^{0.25} \] \hspace{1cm} (11)

where $f$ and $s$ indicates air and steel respectively. This equation has been used by Morales et al.\(^6\) for Stelmor cooling practice and very good result was obtained. However for the present work the following correlation given by Campbell et al.\(^7\) have been used:

\[ h_{c} = 0.683 \left( \frac{k}{D} \right)^{0.466} \left( \frac{C_{p} \mu}{\mu} \right)^{1/3} \] \hspace{1cm} (12)

where $k$ is the thermal conductivity of steel, $D$ is the diameter of the rod, $\rho$ and $v$ are the density and velocity of air respectively, $\mu$ is the kinematic viscosity and $C_{p}$ is the heat capacity of steel.

### 3.2. Phase Transformation Model

It has been assumed that the austenite to ferrite, pearlite and bainite transformation kinetics obey the Avrami\(^5\) type equation:

\[ X = 1 - \exp(-k t^{n}) \] \hspace{1cm} (13)

where $X$ is fraction transformed, $t$ is time and $n$ and $k'$ are the kinetic constants. It has been observed that the value of $n$ depends upon the site of nucleation (whether grain boundary, grain edge or grain corner)\(^8\) and can be treated as constant for a particular transformation. The $k'$ however
is a function of temperature and changes during the course of transformation. It has been proposed by Leroy et al.\(^{19}\) that \(k\) can be calculated using a modified Gaussian function of the following nature:

\[
k = P(1) \exp \left[ \frac{-P(2)}{P(3)} \right] \quad \text{.........(14)}
\]

where \(P(1)\) is the maximum value of \(k\), \(P(2)\) is the temperature of the nose of the TTT curve, \(P(3)\) is proportional to the nose width thickness at mid height of the TTT diagram and \(P(4)\) is the sharpness of the curve. Various calculated values of \(P(i)\) has been taken from Leroy's work for different phases. It is well known that the prior austenite grain size (PAGS) affects the kinetics of ferrite and pearlite transformation. The nucleation rate of ferrite at the grain boundary increases as the grain size becomes smaller because that increases the grain boundary surface area per unit volume of material. In the present work the nucleation and growth has not been modeled separately, however the effect of PAGS on \(k\) (as expressed in Eq. (14)) has been captured as it affects the values of \(P(1)\) and \(P(2)\).\(^8\) A smaller PAGS increases \(P(1)\) and \(P(2)\) and that in turn increases the \(k\). Now, an increased \(k\) would increase the transformation rate as expressed through Avrami equation (Eq. (13) in the paper).

It has been assumed that the austenite to ferrite transformation becomes thermodynamically possible below \(Ar_c\). temperature, the amount of ferrite formed is limited by the equilibrium conditions. The maximum ferrite that can form at a particular temperature is calculated by applying the lever rule to the phase diagram. Pearlite can form below the \(Ar_p\) temperature but only when the amount of carbon in the remaining austenite exceeds the extended Acem line of the phase diagram.\(^10\) A phase diagram was constructed taking into account the effect of all the alloying elements and considering paraequilibrium following the work of Hasiguchi.\(^11\) It was assumed that thermodynamically bainite transformation starts when the temperature of the material goes below \(B_s\) temperature, however, the kinetic parameters like \(k\) or \(n\) are different from that used in ferrite or pearlite. The value for \(B_s\) was calculated following a standard empirical equation.\(^12\) the amount of carbon used in the empirical equation for calculating the \(B_s\) was calculated taking into consideration of the carbon partitioning during austenite to ferrite transformation. For all the transformations discussed so far the fraction transformed was calculated using the work of Agarwal and Brimacombe\(^1\) that uses the concept of virtual time in order to take care of the transformation during continuous cooling. The value of the kinetic constant \(n\) for ferrite, pearlite and bainite are taken to be 1.5, 1 and 1 respectively following the work of Donnay et al.\(^9\)

The kinetics of martensite transformation is assumed to follow the equation proposed by Koistinen and Marburger\(^{13,14}\):

\[
X = 1 - \exp\left(-\frac{M_s - T}{\Delta T}\right)^n \quad \text{.............(15)}
\]

where \(X\) is the fractional transformation, \(T\) is the temperature of steel and \(h\) and \(n\) are constants. Martensite transformation start temperature was calculated using a standard empirical equation.\(^14\) While calculating the \(M_s\) temperature, the effect of carbon partitioning due to other transformation has been taken into account. The value of \(h\) and \(n\) was taken to be 0.011 and 1 respectively.

3.3. Model for Prediction of Hardness

The description of the heat transfer and the phase transformation model developed to predict the thermal profile and the fraction of various phases in the wire rod has been given in the preceding section. Information from these two models, however, can be further used to predict the mechanical properties of the wire rod (i.e. hardness) following the work done by Maynier et al.\(^{15}\) They have developed their model based on a large number of data which can predict the hardness of martensite, bainite and the aggregate of ferrite and pearlite as a function of chemistry and cooling rate. The equation developed by Maynier and co-workers can predict the hardness of these phases (martensite and bainite) both under tempered and non-tempered conditions. The hardness of the individual phases calculated using these equations was then used to predict the overall hardness of the rod using the law of mixture:

\[
H_v = X_m H_{vm} + X_b H_{vb} + (X_m + X_b) H_{vm+p} \quad \text{.............(16)}
\]

where \(H_v\) is the total hardness in Vicker’s scale, \(X_m\), \(X_b\), \(X_p\) and \(X_c\) are the volume fraction of martensite, bainite, pearlite and ferrite respectively; and \(H_{vm}\), \(H_{vb}\) and \(H_{vm+p}\) are hardness of martensite, bainite and mixture of ferrite and pearlite respectively. The fraction of the various phases was separately calculated for all the finite difference nodes used in the heat transformation model and thus the hardness was also similarly predicted at all the nodes. This enables the model to predict the hardness profile precisely at various positions inside the wire rod which would be particularly beneficial for wire rods having a non-homogeneous microstructure.

4. Experimental

4.1. Metallographic Experiments

The samples of TMT rebars with 8 mm, 10 mm and 12 mm diameter were collected from the WRM. The composition range of the TMT bars is mentioned below:

\[
C=0.18-0.22\%, \quad \text{Si}=0.2-0.22, \quad \text{Mn}=0.68-0.72, \quad \text{S}=0.05 \quad \text{and} \quad \text{P}=0.09 \quad \text{max} \quad \text{(all the values are given in wt%).}
\]

These samples were ground and polished following the standard metallographic procedure. The polished specimens were etched with 2% nital to reveal the microstructure of the specimens. The optical micrographs were taken at different magnifications and those were used to measure the amount of different phases with the help of an image analyzer and also to measure the tempered martensite rim thickness. To reveal the finer aspects of the microstructure, photographs were also taken using a JEOL Scanning Electron Microscope at higher magnifications. To get the hardness profile of the samples, micro hardness data were generated using a micro-hardness testing machine with a load of 5 KG. The micro-hardness values were measured at a distance of 0.25 mm from the surface to the center of the wire rods. The hardness values at different points across the section of the wire rod were plotted against the radius of the
4.2. Plant Trials to Validate the Thermal Model

To validate the thermal model, an experiment was conducted in the plant. 8 mm diameter TMT rods were rolled (all having the same composition: C=0.21%, Si=0.22%, Mn=0.68%) at different rolling speeds keeping the other process parameters (soaking temperature, water pressure and the water flow rate in the water boxes) same. Five coils were rolled at each rolling speed and in each case the LHT was measured with the help of an optical pyrometer. As expected the LHT decreased with the decrease in the rolling speed. The details of the experimental data are given in Table 1.

5. Result and Discussion

5.1. Validation of the Thermal Model in the Water Box

The model was run taking the same process parameters, i.e. the soaking temperature of the billets, water flow rate and the water pressure, as input as described in Sec. 4.2. The model predicted LHTs have been plotted against the experimentally determined ones in Fig. 3. The bars in the figure show the range of measured LHTs at various rolling speeds. It can be observed that the model predicted values are in good agreement with the experimental ones.

5.2. Prediction of Martensite Rim Thickness

The accuracy of the predicting capability of the model was also tested with respect to the prediction of tempered martensite rim. A large number of different diameter samples processed with various suitable rolling parameters in WRM were collected. These samples were polished and etched with nital. The tempered martensite rim at the surface takes a darker appearance and that was measured with the help of a scale attached with the eyepiece of an optical microscope. A large number of data were generated for 8 mm, 10 mm and 12 mm TMT rod and it was found that the rim thickness varies over a range of 0.15 to 0.20 mm span. Then the model has been run using different rolling parameters for various diameter rods as typical inputs. It was found that in each case model predicted results fell well within the span of experimentally determined rim thickness. Figure 4 gives a typical output of the model along with the data collected over a period of time for TMT rods having different diameter, the bars indicate the range of experimental data points.

5.3. Microstructure Evolution in the Wire Rod and Validation of Hardness Profile

Figure 5 shows fraction of various phases, as predicted by the model, in the wire rod across its diameter. The lines represent model predicted result and the solid/open symbols indicate the experimentally determined phase fraction near the center region of the wire rod. It is clear that the model predicted values are in good agreement with the experimental ones. The presence of bainite in higher amounts towards the surface of the wire rod makes it difficult to evaluate the phase fraction accurately with the help of an image analyser, so the validation of the model in this region has been done by matching the hardness data with the model predicted hardness profile.

Figure 5 shows that at the surface, there is a layer which is 100% martensite and towards the center the amount of the other phases increases. As expected and observed in the

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Table 1. LHT data with variation in the rolling speed for an 8 mm TMT wire rod.
microstructure, the model also predicts that at the center, ferrite and pearlite are present predominantly along with some amount of bainite (3 to 5%), in between the ferrite-pearlite rich core and martensite rich surface there exists a thin layer rich in bainite.

Figures 6(a) and 6(b) show how at different depths of the wire rod the microstructure evolves with lowering of the temperature. It must be mentioned here that the wire rod stays inside the water box region for about 1 s and for the rest of the time it gets cooled on the Stelmor conveyor. At the center of the wire rod, phase transformation starts with austenite to ferrite transformation, it is to be noted that although the equilibrium temperature (Ar3) for this grade of steel is around 790°C but the transformation starts at about 650°C because of the cooling rate that the rod experiences. The heat of transformation thus developed increases the temperature of the rod by about 10°C before the temperature reduction recommences when the transformation is ~70% complete. The pearlite transformation also starts at around 650°C when the amount of carbon in the remaining austenite exceeds that given by the extended Acm line. However, the sequence of the phase transformation is quite different at a depth of 3.1 mm. In this region, the transformation starts with conversion of austenite to bainite and is followed by the transformation of the remaining austenite to ferrite and pearlite. This is due to the fact that this region experiences a higher cooling rate than that at the center, temperature goes below the Bs before any appreciable amount of ferrite can form. For some time after austenite to bainite transformation, no other transformation takes place at this region (for about 2 s), however, when the rod comes out of the water boxes, the temperature increases and then ferrite transformation starts followed by pearlite as the rod gets cooled on the Stelmor conveyor. The temperature profile of the wire rod at the center, surface and at a depth of 3.1 mm is shown in Fig. 7.

Figure 8 shows the comparison between model predicted and experimentally determined hardness profile in an 8 mm diameter TMT wire rod. It is clear that the model predicted results are in good agreement with the actual ones. There are a few interesting points in the hardness curve. The first dip in the hardness points (marked as A) corre-
sponds to an area where the amount of martensite (tempered) and bainite is less (\(\leq 50\%\) and \(\leq 20\%\) respectively, rest is ferrite). Soon after this region there is a bainite rich area (marked as B in Fig. 7) where there is \(\leq 50\%\) bainite, \(\leq 20\%\) pearlite and the rest ferrite. As the effect of tempering on the hardness reduction of bainite is less \(16)\) and the fine pearlite that forms in this region has considerable hardness, the total hardness of this area is more than the area marked as A. The hardness after this area (marked as B) reduces gradually because of the steady increase in the amount of the softer phase like ferrite at the expense of bainite or martensite. In Figs. 9(a), 9(b) and 9(c), the SEM microstructures of the ferrite–pearlitic rich area (core), the bainite rich region (mid-center) and the tempered martensite layer (surface) in the TMT wire rod are shown respectively.

6. Conclusions

(1) A coupled heat transfer and phase transformation model has been developed which can correctly predict the temperature profile and the phase transformation during wire rod rolling. The heat of recalescence has been included in the heat transfer equation which makes the model capable of predicting the temperature profile of wire rod during any industrial rolling operation correctly while phase transformation is taking place.

(2) The LHT of TMT rebars has been varied by rolling the wire rod at various speeds and keeping the other rolling parameters fixed. It has been found that the mathematical model predicts the LHT at different rolling speed accurately.

(3) It has been shown that the phase transformation kinetics in the TMT rebars at different cross section of the wire rod vary to a great extent because of the difference in the cooling rate at various depths. This is the reason for which this type of wire rod has a gradient microstructure across the diameter which leads to an inhomogeneous hardness profile in the wire rod.

(4) A hardness prediction model has also been developed that calculates the hardness of the individual phases and then using law of mixture evaluates the average hardness of the material at various cross section of the wire rod.

(5) It has been shown that the model is capable of predicting the tempered martensite rim thickness correctly for TMT rebars having different cross sections and it can predict the complex hardness distribution across the diameter of the wire rod accurately.

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