# Batch Annealing Model for Cold Rolled Coils and Its Application

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**Batch annealing is one of the most important processes in cold rolling mills which dominate the final product quality of cold rolled steel sheets. In this study, a new simulation modelling of the batch annealing process was developed by using HeatMod software and verified by experimental data. The required soaking time to reach the desired temperature of cold spot and the surface temperature of steel coils were predicted. The results showed that the batch annealing cycle time can be reduced by about 8-10% resulting in an increase in productivity. The variation of mechanical properties of steel coils can also be greatly improved.**

**Keywords: Batch annealing, Annealing model, HeatMod, Cold spot, Soaking time**

## 1. INTRODUCTION

Extensive deformation given to the steel at room temperature during the cold rolling process significantly reduces the ductility and formability of cold rolled sheets. This necessitates annealing, where the cold rolled sheets get stress relieved through the mechanisms of recovery, recrystallization and grain growth. Annealing of cold rolled steel sheets are carried out either in a continuous annealing furnace, where the sheets after cold rolling enters an integral tunnel type furnace for annealing, or in a batch annealing furnace, where the cold rolled sheets are coiled and subsequently stacked for annealing in a cylindrical furnace.

In the batch annealing process, 3-4 cylindrical steel coils (typically 10-20 t each) are stacked on a furnace base and annealed under a hydrogen atmosphere. The air-gaps between the sheets in the coils result in very low radial thermal conductivity. As a result, spatial variation in temperature is prevalent during the annealing process. The outer surfaces of the coil, referred to as hotspots, are heated faster and achieve the annealing temperature in a shorter time as compared to the inner core of the coil, commonly referred to as cold spot. Since recrystallization and grain growth are thermally activated processes, such thermal lag leads to spatial variation in microstructure, with an associated variation in the mechanical properties within a coil. In addition, due to the axial temperature variation along the furnace, there are coil-to-coil variations in their microstructure and mechanical properties[1].

Although an increase in soaking time usually results in reduction in microstructural and mechanical property variations, it also reduces the furnace productivity. Therefore, selection of soaking time in an industrial batch annealing operation requires an optimization between productivity and quality[2]. In addition, appropriate selection of the heating rate, has a metallurgical implication on precipitation and recrystallization kinetics, as well as annealing temperature from the crux of batch annealing thermal cycle design[3].

The batch annealing operation has a significant influence on all the important plant performance parameters, such as energy consumption, plant productivity and emissions, as well as quality parameters, strength, ductility, drawability, and formability. In view of its relevance on all these key parameters, it is essential to optimize the batch annealing operation for maximum productivity and minimum energy consumption, while achieving the specified product quality. Despite being a critical operation, generally the batch annealing cycles at the industrial scale are designed through plant trials and empirical methods, which in addition to being time consuming and expensive, may at best provide sub-optimal result. Instead, the process cycle can be effectively optimized through an annealing model, which can emulate the batch annealing operation, thus reducing the number of plant trials required for plant optimization.

The annealing simulation model for $H_2$ BAF at China Steel (CSC) is derived from the original model of HNx (H2: 7%, N2: 93%) BAF. However, there are not enough parameters that can be considered in this annealing model for $H_2$ BAF, it can easily lead to

product quality variation. Furthermore, the annealing time for steel coils is not consistent; the lighter coils sometimes require a longer annealing time to that of the heavier coils as shown in Fig.1. This phenomenon resulted in a waste of energy for CSC.
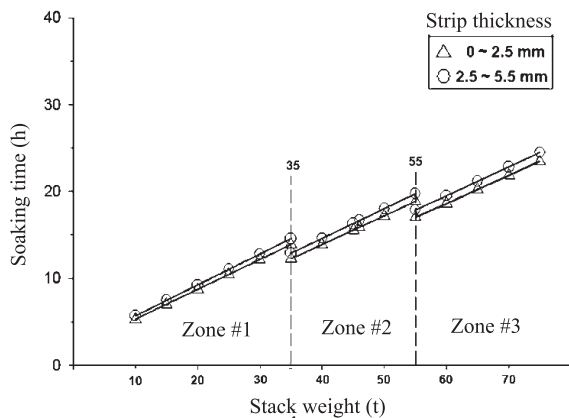


**Fig.1.** Soaking time under different stack weight and strip thickness.

In this study, a new simulation model for the batch annealing process is developed by using HeatMod software and verified by experimental data. The required soaking time to reach the desired temperature of cold spot and the surface temperature of steel coils are predicted. The variation of mechanical properties and the surface quality of steel coils can also be well improved.

## 2. RESEARCH METHOD

### 2.1 Coil temperature measurement system

The BAF annealing was performed by heat transfer. The convector plates between the coils were used to enhance the heat flow. The atmospheric gas during annealing was supplied from the RC fan at the base and flowed into the center of the coil through the convector plate as shown in Fig.2. Because it is impossible to control the uniform temperature of each coil constantly, the cold spot is found through a test to decide the heat-treating cycles lowest temperature.

The temperature of the atmospheric gas is controlled by the thermocouple installed between the inner cover and the coil. The base temperature of the heating furnace is controlled by the measured temperature from the thermocouple installed in the furnace as shown in Fig.2. The arrows show the direction of the circulating atmosphere. The temperature of the cold spot is controlled using a measured temperature. To install the thermocouple for measuring the temperature of the cold spot is a complicated procedure in the heat-treating cycle. Since the base temperature of the heating furnace

was considered nearly the same as the cold spot temperature, it was used as a check point instead of the temperature of the cold spot to control the soaking time during the batch annealing process.
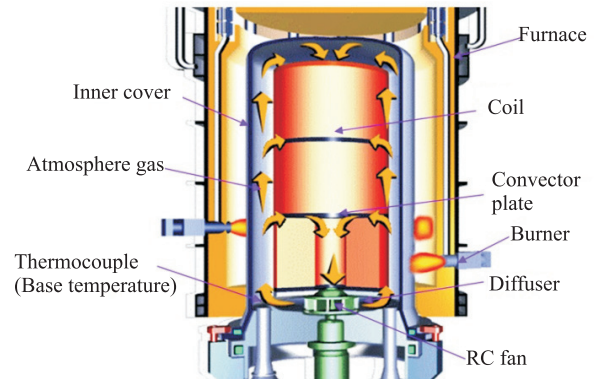


**Fig.2.** Schematic diagram of $H_2$ BAF.

As in BAF annealing the heating and cooling time vary according to the components of the atmospheric gas. There is a mutual relationship between the cold spot temperature and base temperature for the annealing cycle control. So, it is very important to find the cold spot of the BAF, the cold spot of the coil and the variation of the annealing cycle temperature were investigated. In order to decrease the production cost by heat-treating with adequate temperature and to acquire good mechanical properties of the steel sheet by application of adequate soaking time according to the coil width, thermocouples for measuring temperature were installed as shown in Fig.3. Besides, heating the cold spot and cooling the hot spot, various effects such as, homogeneous mechanical properties on the sheet steel are very important, the temperature variation of the two spots were checked in this study.
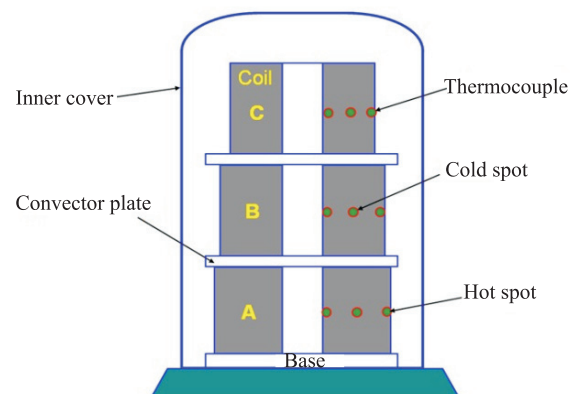


**Fig.3.** Thermocouple position of each coil.

### 2.2 HeatMod

HeatMod is a program for on or off-line calculation of heating and cooling cycles in a bell-type

annealing plant. The objective of the HeatMod is to attain a maximum annealing plant performance through the optimum utilization of furnaces and energy, minimizing the time of annealing and cooling cycles for the desired quality.

For that it utilizes a mathematical model for advance calculations of changes in temperature over time as a function of material and furnace data. The model takes into respect diverse atmospheres ($N_2$, HNX or $H_2$), coil materials and furnace types (e.g. including heating and cooling hoods).

HeatMod considers all the three mechanisms of heat transfer (conduction, convection and radiation) to determine the transient temperature variation inside of the coils and as well as the different furnace components, such as flue gas, furnace wall, protective cover, cooling hood, convector plate, and atmosphere. The output of HeatMod is the complete transient temperature history during the heating and cooling cycles, at different locations of the coil. In the following subsections, equations and solution strategy for some of the components are described.

### 2.2.1 Model for coils

The thermal profiles of coils are obtained through the equation of conduction, solved using the finite difference technique in cylindrical coordinates. Owing to the cylindrical symmetry of the coils, only the radial plane is analyzed. As the temperature varies in the axial direction of the furnace, all the three or four coils stacked in the furnace are analyzed. HeatMod calculates the temperature distribution inside of coils as a function of time by solving Fourier's equation of heat conduction[4]:

$$\rho_m C_m \frac{\partial T_m}{\partial \tau} = \frac{\partial}{\partial z}\left(k_z \frac{\partial T_m}{\partial z}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(rk_r \frac{\partial T_m}{\partial r}\right) \quad\dots\dots\dots (1)$$

where $\rho_m$ is the density, $C_m$ and $k_z$ are temperature dependent specific heat, and conductivity of the coil. $k_r$ is the radial conductivity of the coil, which depends on the sheet thickness and air gap between sheets. Using the appropriate boundary conditions[5], the solution to the above equation provides the complete transient temperature history during heating and cooling cycles, at different locations of the coil.

### 2.2.2 Model for cover hood

The heat flow of convection equations for the gas flowing between the cover hood and the outer coil surface and within the inner coil core are given by:

$$Q_{conv.} = A \cdot \alpha \cdot (T_1 - T_2) \quad\dots\dots\dots\dots\dots\dots (2)$$

$$Q_{transp.} = \dot{M} \cdot C_p \cdot (T_{in} - T_{out}) \quad\dots\dots\dots\dots\dots (3)$$

where $A$ is the cross sectional area, $\alpha$ is the heat transfer coefficient, $T_1$ and $T_2$ are specified high, and low temperature between the gas flow and coil. $\dot{M}$ is the mass flow rate for the outer and inner gas, $C_p$ is temperature dependent specific heat of the gas. $T_{in}$ and $T_{out}$ are the temperature for the inner and outer gas. The variation in gas temperature across the convector plate in the radial direction was obtained by interpolating the outer and inner gas temperatures.

The heat flow of radiation equation for the cover hood and the outer surface of the coil is given by:

$$Q_{radiation.} = A \cdot F \cdot \varepsilon \cdot \sigma \cdot \left(T_{inner\,cover}^4 - T_{coil\,surface}^4\right) \quad\dots\dots (4)$$

where $F$ is the shape factor, $\varepsilon$ is emissivity, $\sigma$ is the Stefan Boltzmann constant. $T_{inner\,cover}$ and $T_{coil\,surface}$ are the temperature of inner cover and outer surface of the coil, respectively.

The coils were divided into grids in the radial and axial directions. Grids for the gases, furnace wall, and cover hood in the axial direction were replicated from the axial grids of the stacked coils. The grid concept of HeatMod to solve the differential equation with the method of finite differences is shown in Fig.4. The surface temperature of the coils, used as a boundary condition, is calculated with the help of balances of thermal fluxes. For each control volume the sum of incoming heat fluxes has to be equal to the sum of outgoing heat fluxes[6]. The governing equations for all the components were solved in sequence and iterated until a global convergence of temperatures was achieved. The transient profile was achieved by marching in time.
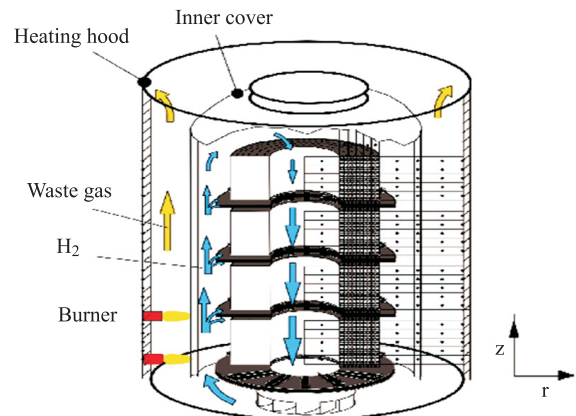


**Fig.4.** Grid concept of HeatMod.

### 2.2.3 Computational process

The flowchart, as shown in Fig.5, resumes the computational algorithm developed to calculate the spatial and temporal evolution of temperature for the coils during the batch annealing operation. The following action diagram shows the flowchart of the calculation.

For given stack geometry, base data and quality specification, HeatMod calculates the heating time, by using the algorithm displayed in Fig.5.

At first the flow distribution of the purge gas is calculated for the given stack geometry and the temperature fields are initialized. After initialization the time iteration scheme starts. For every time step in the algorithm the coil surface temperatures are calculated for a given burner power. The next time step will start, if the gas temperature is identical with a given set-point

value and the temperature distribution in each coil cross section is determined. The heating time is finished if a given cold spot temperature is reached in every stack.

## 3. RESULTS AND DISCUSSION

### 3.1 Coil temperature distributions

A series of experiments have been conducted to investigate the relationship between the soaking time and the temperature variation of hot and cold spots. In this study, the coil temperature distribution was measured and checked by means of the self-developed coil temperature measurement system. A total of 6 cases with various parameter combinations in the present experiments were studied. The experimental boundary conditions (e.g. purge gas flow rate) were all set the same. Table 1 shows the experimental results of soaking
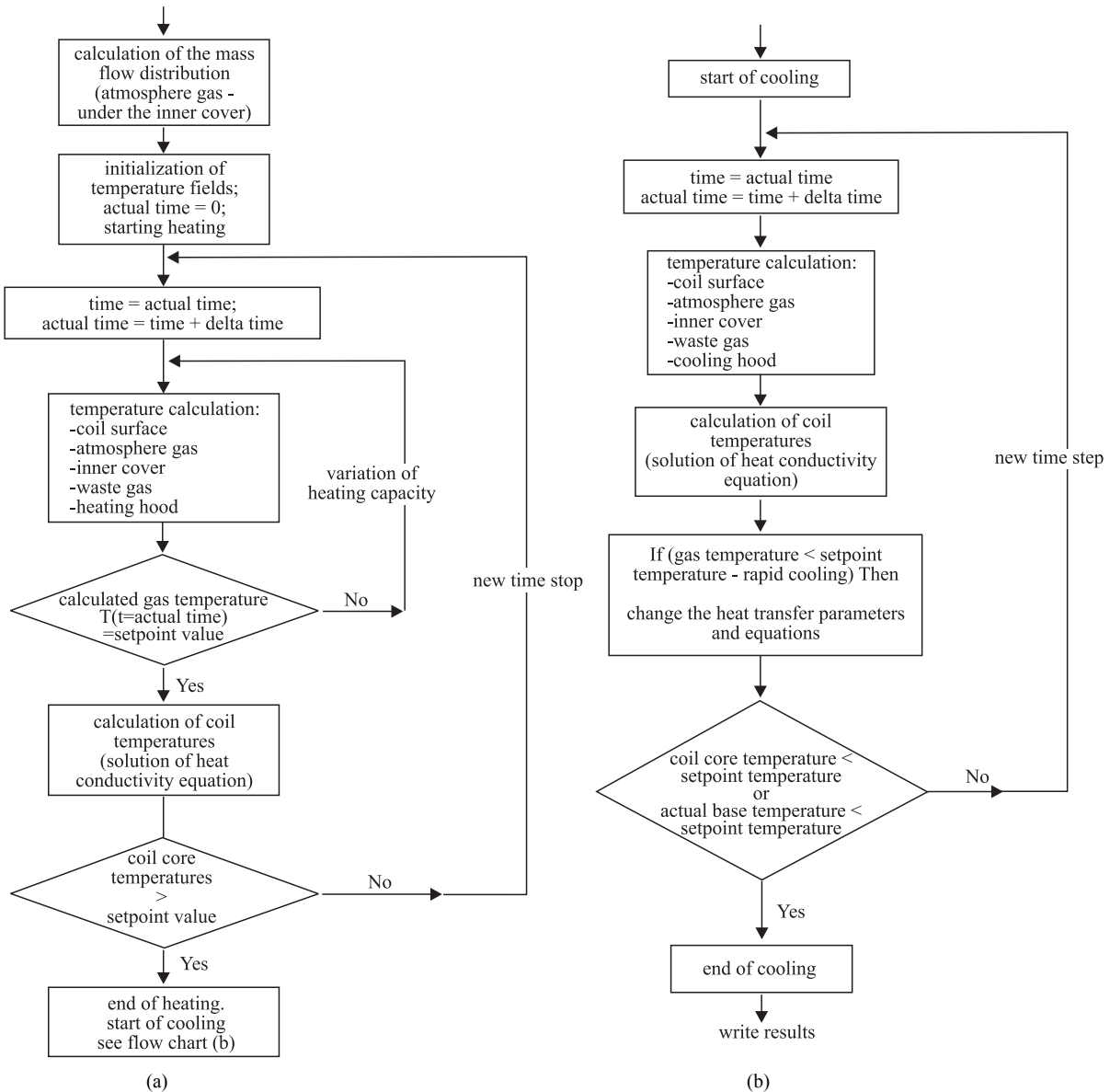


**Fig.5.**  (a) Flow chart of simulation for annealing process (b) Simulation of cooling process.

**Table 1**  The experimental results of the coils during various batch annealing process

| | Coil no. | Stack weight (t) | Soaking time (min) | Annealing time (min) | Cold spot (℃) | Hot spot (℃) | Base (℃) | HRB (present) | HRB standards |
|---|---|---|---|---|---|---|---|---|---|
| High-carbon steel coils | | | | | | | | | |
| 1 | C1 B1 A1 | 36.71 | 406 | 860 | 654 | 688 | 705 | 81 81 81 | |
| 2 | C2 B2 A2 | 38.57 | 433 | 1210 | 691 | 710 | 707 | 82 80 80 | 75-85 |
| 3 | D3 C3 B3 A3 | 51.93 | 730 | 1330 | 680 | 702 | 705 | 82 81 81 81 | |
| Alloy steel coils | | | | | | | | | |
| | Coil no. | Stack weight (t) | Soaking time (min) | Annealing time (min) | Cold spot (℃) | Hot spot (℃) | Base (℃) | HRB (present) | HRB standards |
| 4 | C4 B4 A4 | 36.87 | 414 | 970 | 690 | 716 | 717 | 178 187 176 | |
| 5 | D5 C5 B5 A5 | 48.81 | 555 | 1328 | 678 | 712 | 715 | 179 174 178 176 | 160-195 |
| 6 | D6 C6 B6 A6 | 59.52 | 945 | 1730 | 683 | 714 | 718 | 172 174 170 164 | |

time and mechanical properties (Rockwell Hardness B Scale, HRB) for different steel grades, stack weight and number of coils stacked during the batch annealing process. The base temperature of the heating furnace was used as a check point to control the soaking time during the batch annealing process. In this study, the soaking process for the high-carbon steel and alloy steel coils were stopped when the base temperature of the heating furnace reached above 705°C and 715°C, respectively.

Figure 6 presents experimental results of case 1 for the temperature distributions of coils during the batch annealing process, including the temperature variation of gas and hot and cold spots.

From the results, the desired target hardness for the high-carbon steel and alloy steel were met, when the temperature of cold spots reached above 654°C and 678°C, respectively. Therefore, the cold spot for the experiments of cases 2, 3, 4 and 6 were over heated and the energy during the batch annealing process was wasted.

Owning to the fact that the temperature of the cold spot for each annealing batch was difficult to gather, therefore the base temperature of the heating furnace was usually used instead of the cold spot temperature to control the soaking time during the batch annealing process. However, Table 1 shows the temperature of cold spot is lower than the base temperature ranging

from about 17-46°C, so using the base temperature of the heating furnace to control the soaking time is not precise.
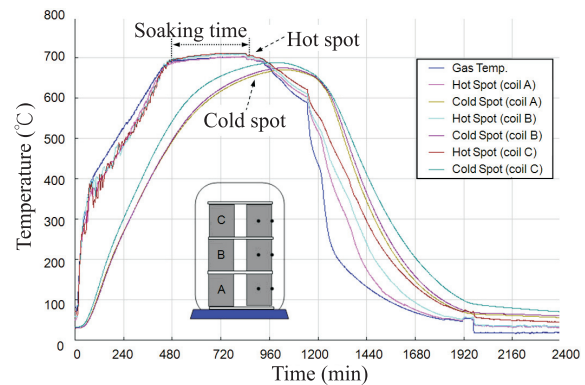


**Fig.6.** Experimental results of case 1 for the temperature variation of gas and hot and cold spots.

### 3.2 HeatMod simulation

In this study, a new simulation model for the batch annealing process is developed by using HeatMod and verified by experimental data. The required soaking time to reach the desired temperature of cold spot and the surface temperature of steel coils are predicted. Figure 7 shows calculated and measured curves for

case 2 experiments for the temperature variation of hot and cold spots over annealing time. The comparison of the predictions evaluated by HeatMod with all the present experimental data was made. The maximum deviation of the results predicted by the HeatMod from the experimental data are 0.58% for the annealing time,

1.15% for the required soaking time to reach the desired cold spot temperature and 0.56% for the variation of hot spot temperature.

Table 2 shows the simulation results of required soaking time for cold spot as calculated by the new simulation model compared with the experimental data
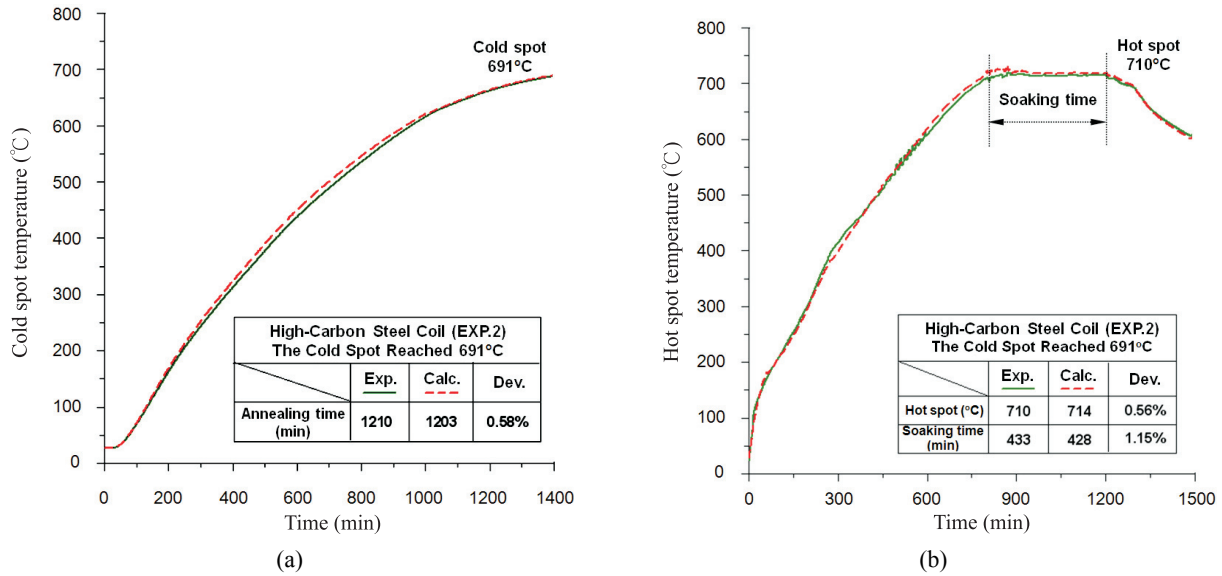


**Fig.7.** The required annealing time to reach the desired cold spot temperature.

**Table 2** HeatMod simulation results of soaking time compared with the experimental data

| | | | | Soaking time (min) | | Soaking time deviation (%) | HRB (present) | HRB standards |
|---|---|---|---|---|---|---|---|---|
| High-carbon steel coils | | | | | | | | |
| | Coil no. | Stack weight (t) | Cold spot (℃) | Experiment (measured) | New HEATMOD simulation model (calculated) | | | |
| 1 | C1 B1 A1 | 36.71 | 654 | 406 | 402 | 0.99% | 81 81 81 | |
| 2 | C2 B2 A2 | 38.57 | 691 | 433 | 428 | 1.15% | 82 80 80 | 75-85 |
| 3 | D3 C3 B3 A3 | 51.93 | 680 | 730 | 738 | 1.11% | 82 81 81 81 | |
| Alloy steel coils | | | | | | | | |
| | Coil no. | Stack weight (t) | Cold spot (℃) | Experiment (measured) | New HEATMOD simulation model (calculated) | Soaking time deviation (%) | HRB (present) | HRB standards |
| 4 | C4 B4 A4 | 36.87 | 690 | 414 | 421 | 1.69% | 178 187 176 | |
| 5 | D5 C5 B5 A5 | 48.81 | 678 | 555 | 547 | 1.44% | 179 174 178 176 | 160-195 |
| 6 | D6 C6 B6 A6 | 59.52 | 683 | 945 | 957 | 1.27% | 172 174 170 164 | |

with different batch annealing cases. A satisfactory agreement is achieved between the results predicted by the simulation model and the experimental data. The maximum and average soaking time deviations of the results predicted by HeatMod from the experimental data are 1.69% and 1.27%, respectively. The reliability of the developed HeatMod had been thoroughly verified by experiments. From the results, we can find the minimum cold spot temperature to meet the mechanical properties and the surface quality of steel coils for the high-carbon steel and alloy steel coils were 654°C and 678°C, respectively.

Table 3 shows the simulation results of required soaking time for specified cold spot as calculated by the new simulation model compared with the original annealing model under different batch annealing cases. The set-point of cold spot for the high-carbon steel and alloy steel coils were 654°C and 678°C, respectively. It was the minimum temperature of coils to meet the mechanical properties and the surface quality of steel coils. From the results, the new simulation model could save soaking time more than the original annealing

model ranging from about 32-80 min. The average soaking time saving for the high-carbon steel and alloy steel coils were 53 min and 56 min, respectively. Consequently, the results show that the batch annealing cycle time can be reduced about 8-10% causing productivity to increase. The variation of mechanical hardness of steel coils can also be well improved.

## 4. CONCLUSION

The conclusions drawn from the results and discussion are presented below:

1. The minimum temperature of cold spot to meet the mechanical properties and the surface quality of steel coils for the high-carbon steel and alloy steel coils were 654°C and 678°C, respectively.
2. The temperature of cold spot are lower than the base temperature ranging from about 17-46°C, so using the base temperature of the heating furnace as the control point to decide the soaking time is not precise.
3. The comparison of the predictions evaluated by HeatMod with all the present experimental data

**Table 3** The simulation results of soaking time during batch annealing process

| | | | | Soaking time calc. (min) | | Time saving (min) |
|---|---|---|---|---|---|---|
| **High-carbon steel coils** | | | | | | |
| | Coil no. | Stack weight (t) | Cold spot setpoint (°C) | Original annealing model | New HeatMod simulation model | Time saving (min) |
| 1 | C1 B1 A1 | 36.71 | | 447 | 402 | 45 |
| 2 | C2 B2 A2 | 38.57 | 654 | 450 | 411 | 39 |
| 3 | D3 C3 B3 A3 | 51.93 | | 768 | 691 | 77 |
| | | Average time saving (min) | | | | 53 |
| **Alloy steel coils** | | | | | | |
| | Coil No. | Stack weight (t) | Cold spot setpoint (°C) | Original annealing model | New HeatMod simulation model | Time saving (min) |
| 4 | C4 B4 A4 | 36.87 | | 418 | 386 | 32 |
| 5 | D5 C5 B5 A5 | 48.81 | 678 | 602 | 547 | 55 |
| 6 | D6 C6 B6 A6 | 59.52 | | 795 | 715 | 80 |
| | | Average time saving (min) | | | | 56 |

was made. The maximum and average soaking time deviations of the results predicted by HeatMod from the experimental data are 1.69% and 1.27%, respectively.

4. The required soaking time for specified cold spot was calculated by the new simulation model compared with the original annealing model. The new simulation model would save on soaking time compared with the original annealing model ranging from about 32-80 min. The average soaking time saving for the high-carbon steel and alloy steel coils were 53 min and 56 min, respectively.

5. A new simulation model for the batch annealing process is developed and verified by experimental data. The required soaking time to reach the desired temperature of cold spot and the surface temperature of steel coils was predicted. The batch annealing cycle time can be reduced by about 8-10% resulting productivity to increase. The variation of mechanical hardness of steel coils can also be significantly improved.

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