The Predictive Model of Decarburization Depth of Heavy Rail Billet Surface

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Abstract. In order to determine the influence of heating technology on the decarburization depth of heavy rail billets, the surface decarburization of U75V and U71Mn heavy rail billets under different heating processes was experimentally studied. According to the experimental results, the predictive model of decarburization depth on the surface of heavy rail billet was established, and the errors between the results of the predictive model and those actually measured were less than 5%.

1. Introduction

Due to the high carbon content of the heavy rail steel, the billet is more sensitive to overheat and over burning when heated at high temperature in the heating furnace, and the phenomenon of decarburization is very likely to occur. The decarburization of the heavy rail billet surface not only damages the material structure of heavy rail, increases the process of removing the decarburization layer, and greatly reduces the metal recovery rate, but also degrades the mechanical properties of heavy rail, leading to poorer surface hardness, wear resistance, and fatigue performance, etc. [1-3]. Therefore, the thickness of decarburization layer of heavy rail is one of the key indexes of its quality, which also sets out higher requirements for the heating quality of billet.

Many scholars have studied the quantitative relationship between the decarburization depth of billet surface and the comprehensive factors such as heating temperature, heating time, furnace atmosphere composition and billet rolling process and so on, so as to optimize and control the production process, in order to reduce the decarburization depth of billet surface as much as possible [4-11].

Although there have been a lot of studies, many methods and parameters are difficult to be applied or popularized in practice due to the constraints of experimental conditions, the difference between mathematical models and industrial producing conditions and so on. Accordingly, it is of great significance and function to conduct in-depth research on the anti-decarburization heating process for specific products under certain operating conditions.

2. The Experiments of Decarburization of Billet Surface under Different Heating Processes

2.1. The Chemical Compositions of Two Kinds of Steel

The grades of the experimental steel billets are U75V and U71Mn, and their chemical composition analysis data are shown in Table 1.
Table 1. Chemical compositions of billets. (%)

|     | C    | Si   | Mn   | P    | S    | V | RH[H] |
|-----|------|------|------|------|------|---|-------|
| U71Mn | 0.699 | 0.237 | 1.171 | 0.011 | 0.009 | - | 1.2×10^{-4} |
| U75V  | 0.745 | 0.602 | 0.873 | 0.029 | 0.006 | 0.071 | 1.1×10^{-4} |

2.2. Experimental Methods
In industrial production, the atmosphere in the heating furnace is controlled by adjusting the fuel air consumption coefficient, and the billet heating temperature is controlled by adjusting the furnace temperature. Four experiments of different heating processes are designed, and the control parameters are shown in Table 2. Other control parameters of the heating furnace remain unchanged.

Table 2. Experimental control parameters of heating processes.

|        | Air consumption coefficient | Soaking section temperature /°C | Heating Time /min |
|--------|----------------------------|---------------------------------|-------------------|
| A      | 1.4                        | 1280                            | 720               |
| B      | 1.4                        | 1280                            | 270               |
| C      | 0.9                        | 1280                            | 270               |
| D      | 1.4                        | 1250                            | 270               |

The control scheme of heating temperature during the experiment was developed according to the characteristics of the heating process of the billet in the multi-stage stepping beam furnace. In industrial production process, when the billet is heated in the furnace, the temperature of the billet surface is gradually raised to the target temperature according to different heating speeds, and then the billet is heated for a certain period of time. In order to investigate the influence of different heating processes on the decarburization of the heated billet surface, the heating experiments were conducted by heating different samples at different heating speeds to different target temperatures. The heating speed was selected in 4 states: 4°C/min, 6°C/min, 8°C/min and 10°C/min. The heating temperature was selected in 8 states: 700°C, 800°C, 900°C, 1050°C, 1100°C, 1150°C, 1200°C and 1250°C. Each state was held for 5 minutes.

The decarburization depth of heavy rail billet surface was measured according to GB/T224-2008.

3. Experimental Results and Discussion

3.1. Experimental Results
Comparison of decarburization depth values of the two steel billets surface, U75V and U71Mn, under different heating processes is shown in Figure 1. The experimental results of decarburization depth of U75V billet and U71Mn billet under different heating speeds are shown in Table 3 and Table 4.

Figure 1. Decarburization of two steel billets surface under different heating processes.
3.2. Discussion of Experimental Results

Under the same production conditions, the decarburisation of U75V is more serious than that of U71Mn, and the average decarburization depth of U75V is more than 11% higher than that of U71Mn. In the four experimental processes, for U75V, the production effect of Process D is the best, while for U71Mn, Process B is the best. The heating process experiments determined that the furnace temperature in the soaking section for U75V production should not exceed 1250°C, while the furnace temperature of U71Mn production could reach 1280°C.

With the experimental results of Process A and Process B compared, it is shown that the longer the heating time in the furnace, the more serious the decarburization. In industrial production process, the time of billet heating is restricted by the target heating temperature and the subsequent rolling rhythm, so it cannot be shortened at will. However, for the specific production line, the optimal residence time control parameters can be determined.

The experimental results show that when the heating temperature increases, the decarburization depth on the billet surface of the U75V steel increases, while that of the U71Mn steel decreases. Based on the current conclusions [13-14], the reason for the opposite change of U71Mn steel can be explained as the oxidation reaction occurring on the surface of the casting billet at the same time. As the temperature increases, the oxidation rate increases, and the oxidation rate is greater than the decarburization rate, so the measured decarburization depth decreases instead.

As was mentioned earlier, in the process of industrial production, the atmosphere in the furnace is usually controlled by adjusting Kac, the coefficient of fuel and air consumption. If Kac=1, it indicates that the combustion air supplied into the furnace is just the theoretical calculation amount needed for the complete combustion of the fuel. In other words, the oxygen in the furnace is just burned out, and the combustion of the combustible components in the fuel is also completed. If Kac>1, it indicates the existence of excess oxygen in the furnace, and if Kac<1, it indicates the existence of excess combustible components such as CO in the furnace. In order to ensure the full utilization of fuel and meet the technical requirements of safety and environmental protection, generally Kac should not be too low. The Kac of conventional heating furnace is usually about 0.95-1.2. In our experiments, the extreme states of 0.9 and 1.4 were selected for the Kac, the maximum range of possible adjustment in industrial production.

The experimental results show that for U75V steel, reducing Kac is conducive to reducing the decarburization depth of the billet surface. For U71Mn steel, the effect is just the opposite. The reason may be that the surface oxidation rate of U71Mn billet is higher than the decarburization rate due to the increase of oxygen content, so the measured decarburization depth decreases instead.

Under the same heating process, U75V steel is more liable to be decarburized than V71Mn steel. V71Mn steel begins to form a decarburization layer above 900°C, while U75V steel, at 700°C, and
The decarburization depth of U75V steel is also deeper than that of V71Mn steel. When the heating temperature of U75V steel and V71Mn steel reaches above 1200°C, the decarburization depth increases significantly. According to the above data, coupled with the temperature rising curve of the billet in the heating furnace, it can be determined that the key factor controlling the formation of the decarburization layer is the temperature of the soaking section, which can be effectively controlled by the residence time of the billet in the soaking section.

4. The Predictive Model of Decarburization Depth of Heavy Rail Billet Surface

There is a linear relationship between the degree of decarburization and the square root of heating time [4], as shown in Eq. (1).

$$\delta = a + b \sqrt{t}$$  \(1\)

where, \(\delta\) is decarburization depth (mm), \(a, b\) are coefficients, \(t\) is heating time (min).

The calculating coefficients of U75V and U71Mn can be obtained by substituting the experimental results into Eq. (1), as shown in table 5.

There is an exponential relationship between the degree of decarburization and the heating temperature, as shown in Eq. (2) [12].

$$\delta = ce^{d/T}$$  \(2\)

where \(\delta\) is decarburization depth (mm), \(T\) is absolute temperature (K), \(c, d\) are the experimental coefficients related to the grade of steel, \(e\) is natural logarithm base.

By substituting the experimental data into Eq. (2), the coefficients \(c\) and \(d\) can be obtained, as shown in Table 5.

**Table 5.** Calculating coefficients in Eq.1 and Eq.2.

|       | a   | b   | c     | d     |
|-------|-----|-----|-------|-------|
| U71Mn | -0.197 | 0.107 | 2149  | 10432 |
| U75V  | -0.747 | 0.111 | 33    | 5155  |

Considering the influence of heating temperature and heating time on the decarburization of the billet surface, the predictive model for the decarburization depth of billet surface can be established based on the experimental results. The heating time was characterized by the heating rate \(X\) (°C/min). If atmosphere environment in the furnace was in a normal state during the heating process, when the billet was heated from room temperature to heating temperature \(T\) at a fixed heating rate \(X\), the calculated mathematical description of the decarburization depth of the billet surface was as follows:

$$\delta(X,T)=\begin{cases} a_1+a_2(T/X)^{1/2}+a_3e^{a_4(T+273)} & 900°C \leq T \leq 1250°C , X>1°C/min \\ 0 & T<900°C \end{cases}$$  \(3\)

where \(T\) is temperature (°C), \(X\) is heating rate (°C/min), \(a1 - a4\) are coefficients.

When the billet is heated from the temperature \(T_1\) to the temperature \(T_2\), the depth increment of the decarburization layer is:

$$\Delta\delta=\delta(X_2, T_2)-\delta(X_1, T_1), (T_2>T_1)$$  \(4\)

When the billet is gradually heated from room temperature through \(i\) (i>0) heating rate to temperature \(T\), the total depth of decarburization layer is the algebraic sum of the depth increment formed by the decarburization layer in each heating section:

$$\Delta\delta=\sum\Delta\delta_i$$  \(5\)
Where $\Delta \delta$ is the total depth of decarburization layer (mm), $\Delta \delta_i$ is the decarburization depth in the $i$th heating stage (mm).

When the billet is kept warm for $t$ minutes at the heating temperature $T$, the increment of the decarburization depth of the billet surface can be calculated mathematically as follows:

$$\Delta \delta = a_5 T \sqrt{t} \quad (900°C \leq T \leq 1250°C, \quad t \geq 0) \quad (6)$$

where, $T$ is heating temperature (°C), $t$ is residence time (min), $a_5$ is coefficient.

If the billet heating process is divided into $j$ heating sections and $k$ heat retaining sections, the final decarburization depth is the incremental algebraic sum of the depth of each segmental decarburization:

$$\delta = \sum \Delta \delta_i + \sum \Delta \delta_k \quad (7)$$

The values of each coefficient obtained through the calculation of experimental data are shown in Table 6.

|       | a1   | a2  | a3       | a4     | a5     |
|-------|------|-----|----------|--------|--------|
| U71Mn | -0.395 | 0.0233 | 192.3318 | -8200  | 5.86×10^-5 |
| U75V  | -0.426 | 0.0259 | 112.6238 | -7200  | 6.75×10^-5 |

5. Comparison between Results of Predictive Model and Those Actually Measured

5.1. Heating Sequence of the Billet

During the actual heating process of the billet, the heating sequence is as follows:

1. The billet was preheated at the heating rate of 10.5°C/min, from room temperature to 283°C.
2. The billet was heated at the heating rate of 7.3°C/min, from 283°C to 672°C.
3. The billet was heated at the heating rate of 1.4°C/min, from 672°C to 1230°C.
4. The heated billet was preserved at 1230°C for 249 min.

5.2. The Predicted Model Result of Decarburization Depth on Heavy Rail Billet Surface

According to the predictive model established above, the predicted value of the decarburization depth of U75V billet can be calculated according to the following steps:

1. In the preheating and the first heating section, according to Eq. (3), because of $T<900°C$, so there are:

$$\Delta \delta_1 = \Delta \delta_2 = 0 \quad (mm) \quad (8)$$

2. In the heating section and the soaking section:

It can be seen from Table 6, $a_5=6.75×10^-5$, substituted it into Eq. (6), and there is:

$$\Delta \delta = 6.75×10^{-5} \cdot T \cdot t^{1/2} \quad (9)$$

In the second heating section, there are:

$$\Delta \delta_3 = \delta(1.4,1230) - \delta(1.4,672) = 1.277 - 0 = 1.277 \quad (mm) \quad (10)$$

In the second soaking section, there are:

$$\Delta \delta_4 = 6.75×10^{-5} \cdot 1230 \cdot 249^{1/2} = 1.31 \quad (mm) \quad (11)$$

5. The final depth of decarburization of billet surface after being heated:

$$\delta = \sum \Delta \delta_i = 0 + 0 + 1.277 + 1.31 = 2.587 \quad (mm) \quad (12)$$

The actually measured result of U75V billet is 2.67mm. Compared with the result of predictive model, the error is less than 5%.
Likewise, by using the coefficients corresponding to U71Mn (see Table 6), the decarburization depth of U71Mn billet, after being heated, of predictive model can be calculated:

$$\delta = \sum \Delta \delta_i = 0 + 0 + 1.117 + 1.137 = 2.254 \text{ (mm)}$$ (13)

The actually measured result of U71Mn billet was 2.22 mm. Compared with the result of predictive model, the error is less than 5%, too.

6. Conclusions

The practical applied results show that the predictive model established in this paper can accurately predict the decarburization depth of heavy rail billet surface under different heating processes. In addition, the predictive model can also be used to optimize the billet heating process in industrial production. Under different heating conditions, the billet will have different temperature rising curves. These temperature rising curves of the billet heating process can be obtained through the analysis of heat transfer process, and then the decarburization depth of the billet corresponding to each temperature rising curve can be calculated with the predictive model. By comparing these results in the predictive model, the optimized heating process can be achieved.

7. References

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