Examination of Slab Temperature Change, Rolling Power and Rolling Capacity in a Hot Strip Mill with Mill Arrangement Equivalent to Semi Continuous Type*

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Synopsis

A mathematical model is proposed for the mill arrangement equivalent to semi continuous type in a hot strip mill. The rolling schedule is arranged so that a slab is rolled from 230 mm into 60 mm in bar thickness by 3 passes roughing with only one reverse mill and 60 mm into 1.2 mm, 2.0 mm, and 2.5 mm in final thickness by 7 passes finishing. The possibility of rolling in this case is analytically examined in due consideration of slab weight, temperature change, rolling power, rolling capacity, and rolling speed. As a result, the rolling of the comparably heavy slab with 30 t/m in unit weight is enabled, and the temperature condition is sufficiently fulfilled. The length of the rolling mill line can be geometrically shortened very much in comparison with the case of other type hot strip mill.

I. Introduction

The total number of the hot strip mills in the world is 133 mills, which can be classified into 69 full and quasi continuous type mills and 64 semi continuous type mills. In Japan, 21 hot strip mills are now in operation. Of these, 9 hot strip mills are the semi continuous type and 10 mills are the full continuous type, and the newest 2 are the quasi continuous type, which is called the three quarters continuous type.

Stating from the historical point of view in the change of the mill type, most semi continuous type mills in Japan had been built before 1962, and then the type of mills was changed from the semi continuous type to the full or the quasi continuous type, i.e., the mill is no longer built. From the historical point of view, in the change of the mill type, most semi continuous type mills in Japan had been built before 1962, and then the type of mills was changed from the semi continuous type to the full or the quasi continuous type, i.e., the mill is no longer built.

The semi continuous type mill is remarkably profitable for the shortness of the rolling mill line length and the simplicity of the mill layout. However, it is impossible to roll the heavier slabs with the semi continuous type mill because the final rolling temperature determined according to the metallurgical requirements cannot be secured, even though the slab is reheated at the maximum allowable temperature. In addition, the semi continuous type mill is insufficient in the rolling capacity and in the energy saving, because the required reheating temperature must be comparatively high, compared with the case of the full and the quasi continuous type. Consequently, some reports to be discussed about the remodelling of this type mill were made. Consequently, some reports to be discussed about the remodelling of this type mill were made.

The usual rolling process in the semi continuous type is that a slab is rolled to the required bar thickness through 5 passes with only one reverse roughing mill, and then travelled to the tandem type finishing train equipped with 6 to 8 mills to reduce to the designated final thickness. The stay time till the next slab enters into the first roughing pass after the previous slab has been rolled in the roughing process is very long, because 5 passes are performed by only one reverse rougher, which is related to the reason that this type mill is insufficient in the rolling capacity. At the same time, such a long stay time brings the large quantity of the heat loss of the slab and the difficulty in the security of the final rolling temperature determined according to the metallurgical requirements in the case of rolling the heavier slabs.

In particular, the heat loss of the slab on the delay table is conspicuously large, because the bar thickness is comparatively thin there, i.e., empirically 20 to 30 mm. Consequently, it was reported that the reheating temperature can be lowered if the bar thickness on the delay table is large to some extent. For the saving energy in the rolling process, the examination may be performed along the direction.

In this paper, a mathematical model that in a hot strip mill with the mill layout to be equivalent to the semi continuous type, a slab is rolled from the initial thickness 230 mm into the bar thickness 60 mm by 3 passes roughing with only one reverse mill, and then from 60 mm into the final thickness 1.2, 2.0, and 2.5 mm by 7 passes finishing is contemplated, and the possibility of the rolling in this case is analytically examined in due consideration of slab weight, temperature change, rolling power, rolling capacity, and rolling speed.

II. Size of Mill, Pass Schedules, and Relation between Rolling Speed and Rolling Time

Hot strip mills, by which the maximum acceptable slab unit weight 15 t, 20 t, 25 t, and 30 t with 1 m in width can be handled, will be considered in this paper. The layout of the rolling mill stands is equivalent to the semi continuous type, i.e., the mill is equipped with only one reversible rougher $R_{1,3,5}$, where 3 passes are performed, and with 7 tandem type finishers ($F_1, F_2, F_3, F_4, F_5, F_6, F_7$). The roughing work roll diameter is assumed to be 1 300 mm, and the finishing work roll diameter from $F_1$ to $F_7$ is 700 mm, respectively.

The pass schedules in the roughing process shown in Table 1 were determined so that the rolling power...
of the reversible rougher during rolling may be equal at each pass. Generally, the bite angle \( \phi \) is shown by the following formula:

\[
\phi = \tan^{-1} \sqrt{AH/R}
\]

where, \( AH \): reduction per pass  
\( R \): roll radius.

Hence, the bite angle is 18.2, 16.2, and 14.7 deg at the first, the second, and the third pass. The bite angle 18.2 deg is rather large, but is not considered to cause any trouble in operation from Refs. 13) and 14).

As shown in Table 1, the slab entrance velocity into the rougher is 1.0 m/s at each pass. Assuming that the exit velocity at the final finisher \( F_7 \) is 12.0 m/s, the entrance velocity at the first finisher \( F_1 \) should be 0.24 m/s for producing the hot coils with the final thickness \( H_{FF}=1.2 \) mm, and consequently 0.4 m/s for the final thickness \( H_{FF}=2.0 \) mm. The value of \( TL \) in Table 2 indicates the table length required between the exit of the reheating furnace and the rougher, and the value of \( DL \) shows the stand interval between the rougher and the first finisher.

As the same slab with the different length is twice travelled there, the value of \( TL \) and \( DL \) is set as follows.

\[
TL = ML(1)+ML(3)+2VOUT(3)+X(3)......(1)
\]

\[
DL = ML(4)+2VOUT(4)+X(4)................(2)
\]

Where \( ML \) (1) and \( ML \) (3) indicate the slab length before the first and the third pass in the roughing process: \( ML \) (4) is the slab length before the first pass in the finishing process: \( VOUT \) (3) and \( VOUT \) (4) show the slab exit velocity after the second and the third pass: \( 2VOUT \) (3) and \( 2VOUT \) (4) are the distance, in which the slab is travelled in 2 s with the velocity \( VOUT \) (3) and \( VOUT \) (4), respectively: \( X \) (3) is the required distance, in which the slab is decelerated at 0.4 m/s² from the exit velocity after the second pass to zero, and \( X \) (4) is the distance, in which the slab is decelerated at 0.4 m/s² from the exit velocity after the third pass to the entrance velocity at the first finisher.

The finishers are installed in tandem at an interval of 5.5 m, respectively. But, the table length between \( F_1 \) and \( F_2 \) is set at 20 m, because the slab thickness 60 mm at the first pass in the finishing process is a little too large for the shearing performance by a crop shear. Accordingly, in this mill the crop shear is assumed to be installed between \( F_1 \) and \( F_2 \).

Table 2 indicates the pass schedules in the finishing process, where the slab is rolled from the bar thickness 60 mm to the final thickness 1.2, 2.0, and 2.5 mm by the 7 finishers.

Figure 1 shows the time passage, in which the top- and bottom-end of a slab with the weight 30 t/m travels from the position of the exit of the reheating furnace, through 3 passes at \( R_{1,3} \), to the entrance of \( F_1 \) for the case of the various final thickness. This figure shows that the time process to the end of the third pass at \( R_{1,3} \) is the same in disregard of the final thickness for the slab top-end and the bottom-end, because the pass schedule and the velocity schedule in the roughing process are the same. However, the travelling time from the end of the third pass at \( R_{1,3} \) to the entrance of the first finisher \( F_1 \) differs according to the final thickness. The difference of the required time, in which the slab top-end and the bottom-end arrive at \( F_1 \), becomes larger as the final thickness becomes thin. This widens conspicuously between the exit of \( R_{1,3} \) after the third pass and the entrance of \( F_1 \).

Figure 2 shows a velocity diagram of the slab on the delay table. The solid line in this figure is the diagram for the slab top-end, and the dotted line for the bottom-end. The acceleration can be performed, as soon as the slab top-end is wound in the case of the final thickness less than 3.7 mm. The point \( A_s \) in this figure means the beginning point of the acceleration and \( A_e \) the ending point for the slab bottom-end. The time \( T_{DT} \) and \( T_{DB} \) required for the slab top-end
Transactions ISIJ, Vol. 22, 1982 (41)

and the bottom-end, travelling from the exit of R1,2,3 after the third pass to the entrance of the first finisher F1, can be calculated as follows:

\[ TD_{TrVOML(4)}UT(4) + 2 VVOUT(4) + \frac{\Delta d}{d} \] ..........................(3)

\[ DL-LDD-X(4) LDD-Xa \]

\[ Vd \] ..........................(4)

here \( V_d \) and \( V_a \) indicate the slab entrance velocity into the first finisher before and after the acceleration. The length \( L_{DD} \) from the point \( A_s \) to the first finisher \( F_1 \) can be given as follows:

\[ L_{DD} = ML(4) - [20 \cdot HF(2) + 5.5 \cdot HF(1)] + H_{FP}\cdot L_{HR}]/HF(1) \] ..........................(5)

where \( HF(1) \) indicates the slab thickness at the entrance of the \( I \)-th finisher: \( HF(1) \) is, for example, the slab thickness on the delay table, i.e., 60 mm in this case. \( L_{HR} \) shows the length of the hot run table, and \( H_{FP} \) is the final thickness. On the conditions that \( L_{HR} \) is 120 m, the maximum acceptable slab weight is 30 t/m, and the slab is rolled into the final thickness \( H_{FP} = 1.2 \text{ mm} \) by the pass schedules shown in Table 2, \( L_{DD} = 50.14 \text{ m} \) is obtained. The acceleration time \( \tau_a \) is 15 s in the case that the slab velocity on the hot run table is accelerated from 12 to 18 m/s at 0.4 m/s\(^2\). \( V_d = 0.24 \text{ m/s} \) and \( V_a = 0.36 \text{ m/s} \), because the bar thickness is 60 mm and the final thickness is 1.2 mm. Besides, \( VOUT(4) \) is 1.75 m/s and \( DL = 71.36 \text{ m} \), as shown in Table 1. Consequently, the time \( T_{DB} \) for the slab bottom-end and the time \( T_{DD} \) for the slab top-end are finally calculated by using the Eqs. (3) and (4). As a result of the calculation, \( T_{DB} = 218.3 \text{ s} \), \( T_{DD} = 55.0 \text{ s} \).

In conclusion, the time difference between \( T_{DB} \) and \( T_{DD} \) amounts to 163.3 s. However, the time difference becomes smaller with the increase of the final thickness and with the decrease of the maximum acceptable slab unit weight.

### III. Relation between Reheating Temperature and Final Rolling Temperature

In a hot strip mill, the security of the final rolling temperature of the sheet steel, which is determined according to the metallurgical requirements of the steel, is one of the most important factors to guarantee the stable mechanical quality of the products. As indicated in Table 1 in the previous chapter, the length of the rolling mill line of the hot strip mill can be ex-

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### Table 2. Reduction schedules in finishing process.

<table>
<thead>
<tr>
<th>Finishes</th>
<th>( F_1 )</th>
<th>( F_2 )</th>
<th>( F_3 )</th>
<th>( F_4 )</th>
<th>( F_5 )</th>
<th>( F_6 )</th>
<th>( F_7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab thickness (mm)</td>
<td>60.00</td>
<td>29.16</td>
<td>15.75</td>
<td>9.32</td>
<td>6.00</td>
<td>4.18</td>
<td>3.13</td>
</tr>
<tr>
<td>Reduction ratio (%)</td>
<td>—</td>
<td>51.4</td>
<td>46.0</td>
<td>40.8</td>
<td>35.6</td>
<td>30.3</td>
<td>25.1</td>
</tr>
<tr>
<td>Slab thickness (mm)</td>
<td>60.00</td>
<td>28.00</td>
<td>14.30</td>
<td>8.01</td>
<td>4.97</td>
<td>3.38</td>
<td>2.50</td>
</tr>
<tr>
<td>Reduction ratio (%)</td>
<td>—</td>
<td>53.3</td>
<td>49.8</td>
<td>44.0</td>
<td>38.0</td>
<td>32.0</td>
<td>26.0</td>
</tr>
<tr>
<td>Slab thickness (mm)</td>
<td>60.00</td>
<td>28.00</td>
<td>11.63</td>
<td>5.81</td>
<td>3.26</td>
<td>2.08</td>
<td>1.50</td>
</tr>
<tr>
<td>Reduction ratio (%)</td>
<td>—</td>
<td>53.3</td>
<td>58.5</td>
<td>50.0</td>
<td>43.9</td>
<td>36.2</td>
<td>27.9</td>
</tr>
</tbody>
</table>

Fig. 1. Time process of top- and bottom-end of slab with 30 t/m in unit weight travelling from reheating furnace to the first finisher \( F_1 \).
tremely shortened in comparison with other types of hot strip mills, because only the 3 passes roughing is performed in the roughing process. However, there is no more ground to discuss this type mill without examining whether the slab can be rolled in the metallurgically allowable temperature range.

The temperature of the slab reheated in reheating furnace drops by the radiation and convection to atmospheric surroundings. The calculation methods of the slab temperature change have been already reported.\(^7\)\(^-\)\(^10\) In this paper, it has been calculated as an unsteady problem by rewriting the one-dimensional differential equation for transient conduction in the finite difference form assuming that the heat transmission occurs only along the slab thickness direction.

The calculation method of the slab temperature change is as follows; in the case of the thick slab as in the roughing process, the calculation of the slab temperature change is performed by taking only the heat generated by the plastic deformation into consideration in disregard of the heat loss by the contact with the rolls, and of the friction heat generated by the surface slip between the slab and the rolls, because the region of the influence of the contact heat loss, and of the friction heat is considered to be limited only in the vicinity of the slab surface. However, in the case of thin slab as in the finishing process, the heat generated by the plastic deformation, the heat loss by the contact with rolls, and the friction heat by the slip between the slab and rolls should be taken into account. The details about this calculation method may be found in Refs. 9) and 11).

The other assumptions and conditions adopted for the calculation are as follows:

- The rolled material is the killed steel containing 0.08\% carbon, and its specific weight \(\gamma\) is 7800 kgf/m\(^3\).
- As the heat conductivity \(\lambda\) kcal/mh°C and the specific heat \(c\) kcal/kg°C depend on the kind of the steel and on the temperature, their values indicated in the special report\(^13\) published in ISIJ are used in the calculation. The heat transfer coefficient \(\alpha\) for the water jet by descaler is 1000 kcal/m\(^2\)h°C. The descaling time at each pass in the roughing process and at the first finisher \(F_1\) is 4s, and is 2.5s at \(F_2\). The temperature of the water and air is 20°C. Only natural convection is taken into account, and the heat transfer coefficient \(\alpha_h\) = 7.2 kcal/m\(^2\)h°C was used.
- The value of the emissibility \(\varepsilon\), which is necessary for the calculation of the heat loss by radiation, is given by the following formula:\(^9\):

\[
\varepsilon = h_0[0.8+0.58\cdot(h_0/h_i-1)]/h_0 \quad \text{...(6)}
\]

where \(h_0\) is the initial thickness of the slab, and \(h_i\) is the thickness of the slab at the \(i\)-th pass.

For the calculation of the heat generated by the plastic deformation at each pass in the roughing and finishing process, it is necessary to give the flow stress \(k_f\) kgf/m\(^2\) of the rolled material. The flow stress \(k_f\) to be a function of the strain, the strain rate, and the temperature \(\theta_m\) °C averaged along the thickness direction of the slab is given as follows:\(^9\):

\[
k_f = 1.15\cdot1.5\cdot10^6\left(1 - \frac{h_{i+1}}{h_i}\right)^{0.2} \cdot \left[1 - \frac{(h_{i+1} - h_i)}{2\cdot R(h_i - h_{i+1})}\right]^{0.1} \cdot \exp\left(\frac{2.850}{(\theta_m - 273)}\right) \quad \text{...(7)}
\]

where, \(h_i, h_{i+1}\): the thickness of the slab before and after \(i\)-th pass.

\(v_i, v_{i+1}\): the entrance and the exit velocity of the slab at the \(i\)-th pass.

The heat conductivity, the specific heat and the temperature of the roll, which were used for the calculation of the contact heat loss, are assumed to be: \(\lambda_r = 21.6\) kcal/mh°C, \(c_r = 0.128\) kcal/kg°C, and \(\theta_r = 50°C\). The friction coefficient between the rolls and the material, which is necessary for the calculation of the friction heat generated by the slip between the rolls and the material in the finishing process, is assumed to be \(\mu = 0.3\). The pass schedules in the roughing and the finishing process are shown in Tables 1 and 2 in the previous chapter.

The velocity schedule, which is necessary to the calculation of the temperature change of sheet steel in the finishing process, is determined by the reduction schedule and the velocity \(V_{FF}\) at the exit of the finishing process. The exit velocity \(V_{FF}\) is assumed to be 12 m/s, and the slab is accelerated at 0.4 m/s\(^2\) to \(V_{FF} = 18\) m/s as soon as the slab top-end is caught by the coiler.

Figures 3 (a) and (b) indicate the relation between the reheating temperature \(\theta_0\) and the mean temperature \(\theta_{F1}\) of the slab top-end and the bottom-end at the entrance of \(F_1\) for the case that the maximum acceptable slab unit weight 30 and 15 t/m. In this figure, the solid lines are for the case of producing the hot coil with the final thickness 1.2 mm, and the dotted lines are for 2.5 mm. This figure shows that the temperature \(\theta_{F1}\) both at the slab top-end and the bottom-end increases almost linearly with the reheating temperature \(\theta_0\) independent of the size of the mill and the final thickness. The mean temperature difference between the slab top-end and the bottom-end becomes larger with the decrease of the final thickness, and with the increase of the reheating temperature \(\theta_0\). This tendency is more conspicuous in a larger size of mill, because the difference of the time required for the slab top-end and the bottom-end to be carried from the reheating furnace to the entrance of the first finisher \(F_1\) becomes larger with the increase of the maximum acceptable slab weight, and with the decrease of the final thickness as mentioned in the previous chapter. The relation between \(\theta_0\) and \(\theta_{F1}\) for the slab top-end is considered to be almost invariable in the case of producing hot coils within the range of the final thickness handled in this paper.

Figure 4 indicates the relation between the entrance temperature \(\theta_{F1}\) and the exit temperature \(\theta_{FF}\) of the slab top-end and of the bottom-end in the finishing process under the condition that the slab is reduced from the entrance thickness \(HF\) (1) = 60 mm to the final thickness \(HF_{FF} = 1.2, 2.0, \) and 2.5 mm through 7 passes. The solid lines in this figure are for the case of the slab top-end, and the dotted lines are for the...
This figure shows that $\theta_{RF}$ increases with $\theta_{F1}$, but the increasing rate of $\theta_{RF}$ over $\theta_{F1}$ is different substantially between the slab top-end and the bottom-end and changes with the final thickness, too. The increase of $\theta_{F1}$ is considered to raise $\theta_{RF}$ almost linearly for the case of the slab top-end, but such an effect disappears with the decrease of the final thickness.

On the other hand at the slab bottom-end, $\theta_{RF}$ increases more notably with the increase of $\theta_{F1}$ than at the slab top-end, because the slab is accelerated at 0.4 m/s² from the exit velocity 12 to 18 m/s, as soon as the slab top-end is caught by the coiler. The first reason is that the heat loss at the slab bottom-end by the contact with rolls is smaller than that at the top-end, as the contact time of the slab bottom-end with rolls is shorter than that of the top-end. The second reason is that the relative velocity in the contact surface between the bottom-end and rolls is large in comparison with the case of the top-end. The third reason is that the heat generated by the plastic deformation at the bottom-end becomes larger than at the top-end, as the value of $k_f$ given in Eq. (7) increases with the increase of the strain rate.

Figure 5 indicates the relation between the maximum acceptable slab weight $G$ t/m and the reheating temperature $\theta_0$ required to guarantee the final rolling temperature $\theta_{RF}=830^\circ$C at the slab top-end when the slab is rolled from the initial thickness 230 mm to the bar thickness 60 mm through 3 passes with only one reverse mill, and 60 mm to the final thickness $H_{RF}=1.2, 2.0$, and 2.5 mm by the 7 passes finishing. This is derived from Figs. 3 and 4. This figure shows that $\theta_0$ increases gently with $G$, and that the required reheating temperature $\theta_0$ for the case of...
producing hot coils with the final thickness $H_{FF}$ more than 2.0 mm can be lowered less than 1 000°C.

The temperature distribution along the rolling direction from the slab top-end to the bottom-end will be analysed as follows: The slab temperature from the top-end toward the bottom-end decreases gradually in the temperature range of 5°C at most, because the exit velocity at the last finisher is assumed to be invariably 12 m/s in this case till the slab top-end is caught by the coiler. However, the temperature of the slab element passing the finishing train during accelerating rises, because the acceleration begins as soon as the slab top-end is wound. And then, the slab temperature begins to decrease to the bottom-end again after the acceleration to the maximum exit velocity 18 m/s in this case. Therefore, it is very important to examine the final rolling temperature of the slab bottom-end in order to guarantee the good mechanical quality of the hot coil.

Figure 6 indicates the relation between the final rolling temperature at the slab bottom-end and the maximum acceptable slab weight $G$ for the case of the final thickness $H_{FF}$=1.2, 2.0, and 2.5 mm, when the final rolling temperature at the slab top-end is kept at the $A_3$ critical point temperature 830°C. As shown in this figure, the final rolling temperature at the slab bottom-end decreases almost linearly with $G$, but for the range of $G$ handled here, the final rolling temperature at the slab bottom-end is above the $A_3$ critical point temperature, even though the temperature of the slab bottom-end at the entrance of the finishing train is lower than that of the slab top-end. The difference of the final rolling temperature between the slab top-end and the bottom-end increases with the decrease of the final thickness. However, the decreasing ratio of the final rolling temperature of the slab bottom-end for the increase of $G$ becomes slightly smaller with the increase of the final thickness.

IV. Rolling Power

1. Rolling Power in Roughing Process

It is widely known that the energy saving in a hot rolling process can be attained mainly by improving the efficiency of the reheating furnace, and by dropping the reheating temperature as much as possible under condition that the final rolling temperature is kept above the $A_3$ critical point temperature. However, dropping the reheating temperature of the slab results in the increase of the flow stress, and therefore in the increase of the rolling power.

In this mill, the slab is rolled from 230 mm to the bar thickness 60 mm through 3 passes at the reversible rougher $R_{1,2,3}$, so it is important to make the rolling power at each pass as equal as possible. Consequently, it is very important to set a suitable reduction schedule at $R_{1,2,3}$.

The main factors for reducing the rolling power are considered to be as follows: One is to raise the reheating temperature, though this may be contrary to the energy saving in the rolling process: The other is to roll the slab at a slow rolling velocity.

Fig. 6. Variation of final rolling temperature at the slab bottom-end due to change in slab unit weight $G$ under condition that $\theta_{FF}$ at the top-end is kept at 830°C in the cases of $H_{FF}$=1.2, 2.0, and 2.5 mm.

Figures 7 (a) to (c) indicate the rolling power $N_R$ kW/m at each pass due to change of the reheating temperature, assuming that the entrance velocity is same at each pass in the roughing process: i.e., $v_0$=1.0, 0.9, and 0.8 m/s, respectively. For this calculation, the rolling equation by von Kármán was used with the formula of the flow stress given in Eq. (7). This figure shows that the increasing rate of the rolling power becomes gradually larger with the decrease of the reheating temperature, and that the decrease of $v_0$ results in the decrease of the rolling power, and the rolling power is almost in proportion to the entrance velocity. In conclusion, it is impossible to attain the decrease of the rolling power and the decrease of the reheating temperature simultaneously. That is to say, it is necessary either to take a power source more than 10 000 kW/m or to roll at a slow entrance velocity.

Figure 8 indicates the relation between the reheating temperature $\theta_0$ and the entrance temperature $\theta_{FF}$ at the top-end of the slab with the maximum acceptable slab weight 30 t/m for the case of producing the hot coil with the final thickness $H_{FF}$=1.2 mm. This figure shows that the difference of the entrance temperature $\theta_{FF}$ is 10°C at most, even though the schedule for the velocity $v_0$ in the roughing process is changed from 1.0 into 0.8 m/s. Therefore, rolling the slab at the slow entrance velocity is considered to be worthy of discussing as one of the methods to decrease the rolling power, if the temperature difference is within such a range.

2. Rolling Power in Finishing Process

The rolling power in the finishing process mainly depends upon the reduction schedule and the velocity schedule. The speed of the revolution of the finishing roll is designed to increase progressively from the first finisher to the later finisher, because each finishing stand is arranged in tandem. The reduction of the slab is scheduled to decrease from the first finisher to the later finisher for the purpose of protecting from the violent fluctuation in the rolling power at each stand.
Figures 9 (a) and (b) indicate the rolling power $N_F$ kW/m in the finishing process in the cases of $H_{FF}=1.2$ mm (a) and 2.5 mm (b). The dotted line in Fig. 9 shows the rolling power calculated on the temperature condition that $\theta_0=1150°C$ for $H_{FF}=1.2$ mm and $\theta_0=950°C$ for $H_{FF}=2.5$ mm, so that the final rolling temperature at the slab top-end may be kept at the critical temperature 830°C. The solid line shows the power calculated on condition that $\theta_0=1250°C$ for $H_{FF}=1.2$ mm and $\theta_0=1050°C$ for $H_{FF}=2.5$ mm, i.e., the slab reheating temperature is raised higher by 100°C than the necessary reheating temperature. As a result, the increase of the reheating temperature is not considered to be effective for lowering the rolling power in the finishing process. Especially for the case of $H_{FF}=1.2$ mm, the rolling power at each finishing stand is almost invariable in spite of changing the reheating temperature. For the case of $H_{FF}=2.5$ mm, its effect can be observed to some extent.

It has been definitely shown by Fig. 9 that there is a significant difference in the rolling power between the slab top-end and the bottom-end. The reason is that the top-end is rolled in the finishing train with the velocity before the acceleration, and that the bottom-end is rolled with the velocity after the acceleration: The rolling velocity of the slab top-end is one and a half as much as that of the top-end. In conclusion, the rolling velocity has much larger effect on the rolling power in the finishing process than the reheating temperature, which differs from the fact that the rolling power in the roughing process varies notably by the reheating temperature.
The larger rolling power after the acceleration should be taken into account, when the rolling power in the finishing process is discussed. The application of the lubrication rolling is considered to be effective for lowering the rolling power in the finishing process, as soon as the acceleration begins, even though it may bring some amount of heat loss.\(^\text{11}\) Or, setting the maximum rolling velocity after the acceleration a little lower is a profitable method for this problem, because the final rolling temperature at the slab bottom-end is higher than that at the top-end as indicated in Fig. 6. That is, the rolling power can be decreased as a natural consequence, if the finish rolling after the acceleration can be performed with the maximum rolling velocity, so that the final rolling temperature at the bottom-end can be kept at 830°C. The examination of the details about it will be reported in the near future.

**V. Rolling Capacity**

The rolling capacity of this type mill discussed in this paper will be examined, though it is considered to be inferior to some extent in comparison with the other type mills.

In this type mill, the slab is rolled through 3 passes at one reversible rougher in the roughing process. And then, it is travelled to the finishing process. Consequently, the rolling capacity \(N\) t/m/h of this mill is given as follows:

\[
N = \frac{G}{T_B + T_1} \tag{8}
\]

where, \(T_B\): the required time, during which previous slab is rolled three times by the reversible rougher \(R_{1,2,3}\) after the slab top-end at the first pass entered into \(R_{1,2,3}\), and its bottom-end finally passes \(R_{1,2,3}\)

\(T_1\): the idle time till the top-end of the next slab enters into \(R_{1,2,3}\) at the first pass, after the bottom-end of the previous one passed the last roughing

\(G\): the slab unit weight.

Figure 10 shows the relation between the time \(T_B\) and the maximum acceptable slab weight \(G\) for the case that the slab entrance velocity \(v_0\) at the reversible rougher is 1.0, 0.9, and 0.8 m/s, respectively, assuming that \(v_0\) is the same at each pass. Figure 10 shows that \(T_B\) increases linearly with \(G\). \(T_B\) can be regarded as the function of \(v_0\) and \(G\) in disregard of the final thickness \(H_{FF}\), while the idle time \(T_1\) changes according to the final thickness \(H_{FF}\), because the entrance velocity at the first finisher should be changed in the final thickness \(H_{FF}\), assuming that the slab exit velocity at the last finisher is set at 12 m/s. In the case of \(H_{FF}=2.5\) mm, for example, the entrance velocity at \(F_1\) should be 0.5 m/s, at which the slab is travelled on the delay table after the 3 passes roughing. Therefore, the time \(T_i\) should be determined so that the top-end of the next slab just during the first pass at \(R_{1,2,3}\) may not come in touch with the bottom-end of the preceding slab on the delay table. That is, \(T_i\) should be set longer with the decrease of the final thickness.

The determination of the idle time \(T_i\) for the case of producing the hot coil with \(H_{FF}=2.5\) mm in a mill, where the slab of the maximum acceptable unit weight 30 t/m can be rolled, will be illustratively mentioned below.

The slab exit velocity after the third pass at \(R_{1,2,3}\) is 1.75 m/s, assuming that the entrance velocity \(v_0=1.0\) m/s. The required time and distance, in which the slab is decelerated at 0.4 m/s\(^2\) from 1.75 m/s to the entrance velocity 0.5 m/s at \(F_1\), are 3.12 s and 3.52 m. The top-end of the next slab enters into the first pass at \(R_{1,2,3}\) in the idle time \(T_1\) after this slab bottom-end passes through \(R_{1,2,3}\). Therefore, the distance \(L\) from the position of \(R_{1,2,3}\) to the point of the bottom-end of the preceding slab after the lapse of \((T_i+t)\) is as follows:

\[
L = 3.52 + (T_i + t - 3.12) \cdot 0.5 \tag{9}
\]

The next slab is decelerated from the exit velocity after the first pass at \(R_{1,2,3}\) to zero in order to reverse the rolling direction. The distance \(L\) and the time \(t\) required for the deceleration from the exit velocity to 0.5 m/s can be easily calculated, \(i.e., L=26.3\) m and \(t=19.1\) s. By substituting these values for Eq. (9), \(T_i=29.6\) s is obtained. Consequently, \(T_i>29.7\) s is required so that the bottom-end of the preceding slab may not come in touch with the top-end of the next slab on the delay table.

For the case of \(H_{FF}=1.2\) mm, \(T_i>79.1\) s is required.

Figure 11 indicates the relation between the rolling capacity \(N\) t/m/h and the maximum acceptable slab weight \(G\) t/m for the case of producing the hot coil with the final thickness \(H_{FF}=1.2\) mm (shown in dotted lines) and \(H_{FF}=2.5\) mm (solid lines). In this calculation, the idle time \(T_i\) is assumed to be invariable: \(T_i=85\) s for \(H_{FF}=1.2\) mm, and \(T_i=35\) s for \(H_{FF}=2.5\) mm, although \(T_i\) changes by \(G\) and \(v_0\), too. For the time \(T_B\) in this calculation, the value indicated in Fig. 10 was used.

Figure 11 shows that the rolling capacity \(N\) gradually increases with \(G\), and that \(N\) is notably affected.
by the final thickness, i.e., the value of $N$ for $H_{FF} = 1.2$ mm is much smaller than the value of $N$ for $H_{FF} = 2.5$ mm.

As mentioned in the previous chapter, roughing with the slower rolling velocity is effective for lowering the rolling power in the roughing process. However, in this case, the decrease of the rolling capacity must be considered as an inevitable consequence.

**VI. Conclusions**

A mathematical model is proposed for the mill arrangement equivalent to semi continuous type in a hot strip mill. The rolling schedule is arranged so that a slab is rolled from 230 mm into 60 mm in bar thickness by 3 passes roughing with only one reverse mill and 60 mm into 1.2, 2.0, and 2.5 mm in final thickness by 7 passes finishing. The possibility of rolling in this case is analytically examined mainly in due consideration of slab temperature change. As a result, the rolling of the comparatively heavy slab with 30 t/m in unit weight is enabled, and the temperature condition is sufficiently fulfilled. The length of the rolling mill line can be geometrically shortened very much in comparison with the case of other type hot strip mill. Other points clarified by this study are as follows:

1. The reheating temperature $\theta_0$ required to guarantee the final rolling temperature $\theta_{FF} = 830^\circ$C at the slab top-end must be raised with the maximum acceptable slab weight $G$. However, the increasing rate of $\theta_0$ for $G$ is comparatively gentle. The rolling is considered to be sufficiently performed with $\theta_0$ lower than 1000$^\circ$C for producing hot coils with the final thickness $H_{FF}$ greater than 2.0 mm in a mill, in which the maximum acceptable slab weight less than 30 t/m can be handled.

2. The final rolling temperature at the slab bottom-end decreases almost linearly with $G$. For $G$ less than 30 t/m, the final rolling temperature at the slab bottom-end is a little higher than at the top-end, although the temperature at the bottom-end at the entrance of the finishing train is lower. The difference of the final rolling temperature between at the top-end and at the bottom-end increases with the decrease of $H_{FF}$.

3. The rolling power in the roughing process must be increased with the decrease of $\theta_0$. However, the decrease of the rolling power can be attained by roughing with the slower rolling velocity.

4. The rolling power in the finishing process is not so notably lowered although $\theta_0$ increases. The rolling power can be decreased, if the finish rolling after the acceleration can be made with the maximum rolling velocity so that the final rolling temperature of the bottom-end is equal to that of the top-end.

5. The rolling capacity increases gradually with $G$. However, it is notably affected by the final thickness.

**REFERENCES**


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Fig. 11. Relation between $G$ and rolling capacity $N$ in the cases of $H_{FF} = 1.2$ mm (dotted line) and $H_{FF} = 2.5$ mm (solid line) due to change in $\theta_0$. 

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