"Examination for Effect of Pass Schedule on Energy Consumption in Rolling Process"

By

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Abstract

The main purpose of this paper is to find out a pass schedule in the finishing process whereby the energy consumption may be reduced to a minimum, and also to examine the possibility of its application to actual operation.

From an analytical examination, such pass schedules where the reduction ratio is equally distributed at each mill have been found to be very effective for saving energy in the rolling process. On the other hand. the pass schedule brings an acute rise both in the rolling power and the rolling force from the earlier stage to the later stage. This tendency becomes remarkable when decreasing the final thickness. However, by applying lubricants to the mill where the rolling power and the rolling force have an extremely high value, the distribution of both among the finishers has been clarified to be flat.

I. Introduction

In a hot strip mill, the security of the final rolling temperature of sheet steel, which is determined according to metallurgical requirements, is one of the most important factors to guarantee the stable mechanical quality of the rolled products. Therefore, the final rolling must be performed above the A_3 critical temperature, and in as low a temperature as possible from the point of view of saving energy[1].

On leaving the last finishing mill, the geometry of the strip is fixed. If the required final rolling temperature is reached, the fully austenitic strip enters the hot run table where it is cooled to a coiling temperature determined mainly by the product's thicknesss, usuallg 570°C to 700°C.

Thus, it is no exaggeration to say that the mechanical and metallurgical qualities of rolled products depend upon the final rolling temperature and the coiling temperature.

In 1962, the maximum slab unit weight was about 10 t/m, but later, with the

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development of steelmaking technique and the adoption of full continuous hot strip mills, slabs of over 20 t/m have been able to be handled. Moreover, the development of a continuous casting technique has enabled the production of heavy weight slabs and promoted the installation of high capacity rolling mills. Now, full continuous hot strip mills capable of rolling slabs exceeding 30 t/m are in operation.

Because the total length of the rolling mill line must be expanded according to the increase of the slab unit weight, the time required for the slab to travel from the reheating furnace to the last finishing mill becomes longer. Consequently, the amount of the temperature drop of the slab increases, and the security of the final rolling temperature, because of the metallurgical requirement of steel, presents a difficulty. On the other hand, slabs should not rise above 1280°C in the reheating furnace since the accumulated oxide scale becomes excessive on the slab surface, and the scale layer melts above this temperature[2].

In the case where the thickness of the hot coil is changed, the reduction schedule is usually kept constant in the roughing process and changed in the finishing process.

In this paper, a calculation method to estimate the temperature change of the strip in the finishing process is first proposed. Secondly, it is discussed how the temperature drops by changing the reduction schedule in the finishing process, when the strip is rolled from 25 mm in bar thickness to 1.2 mm, 1.6 mm, 2.0 mm and 2.5 mm in final thickness by six passes finishing. At the same time, the problems concerning the rolling power and the rolling force at each finishing mill are analytically examined. Thirdly, when the friction coefficient between the strip and rolls is reduced by applying lubricants, the degree of the influence of the friction coefficient on the change in the strip temperature, the rolling power and the rolling force is discussed.

II. Calculation Method of Change in Strip Temperature during Finishing

2. 1 General Concept of Calculation Method

The usual rolling process in a hot strip mill is that a slab is rolled to the required bar thickness in the roughing process after removing the accumulated scale in the reheating furnace by a scale breaker, and then goes to the finishing train through the delay table. The finishing train is equipped with six to eight mills to reduce the bar thickness to the desired final thickness. The finishers are commonly installed in tandem at intervals of 5.5 m, respectively.

The temperature of the strip on each stand interval drops by the convection and radiation from the strip surface. For the calculation of the change in the strip temperature, the convection and radiation should be taken into consideration both in the finishing and roughing processes. However, the approximate calculation method of the temperature change during contact with the rolls differs depending upon the strip thickness. In the case of a thick strip, as in the roughing process, the calculation of the change in the strip temperature may be performed by taking into consideration only the heat generated by the plastic deformation, disregarding the heat loss by the contact with the rolls, and also the friction heat generated by the surface slip between the strip and the rolls, because the region of the influence of the contact heat loss, and of the friction heat may be considered to be limited only in the nearby strip surface. On the other hand, in the case of a thin strip, as in the finishing process, the heat generated by the plastic deformation, the heat loss by the contact with the rolls at low temperature, and the friction heat generated by the slip between the strip and rolls should be taken into account.

The change in the strip temperature during contact with the rolls may be calculated not as an unsteady but as a quasi-steady problem[3]. These three factors may be treated respectively. The details concerning the calculation methods are indicated below.

2. 2 Temperature Drop by Heat Conduction through Contact between Strip and Rolls

The transmission of the heat from the strip to the rolls may be approximately considered only in the thickness direction of the strip. Assuming that there is no temperature gradient in the thickness direction and in the radius direction of the roll before contact with the strip, the temperature of the contact surface between both is given by

$$\theta_0 = \frac{\lambda_1 a_1^{-1/2}\theta_{01} + \lambda_2 a_2^{-1/2}\theta_{02}}{\lambda_1 a_1^{-1/2} + \lambda_2 a_2^{-1/2}} \qquad (1)$$

where, θ_0 : Temperature of contact surface (°C),
θ_{01} : Temperature of strip before contact (°C),
θ_{02} : Temperature of roll before contact (°C),
λ_1 : Heat conductivity of strip (kcal/mh°C),
λ_2 : Heat conductivity of roll (kcal/mh°C),
a_1 : Thermal diffusivity of strip (m^2/h),
a_2 : Thermal diffusivity of roll (m^2/h).

The strip temperature θ (°C) drops by heat transferred from the strip to the rolls at low temperature as the contact time elapses. θ is presented as a function of the depth from the strip surface and the contact time[4], i. e.,

$$\theta = \theta_0 + (\theta_{01} - \theta_0)\,\mathrm{erf}\left(\frac{x}{2\sqrt{a_1 t}}\right) \qquad (2)$$

where, x : Depth from strip surface in thickness direction (m),

t : Contact time (h).

Therefore, the amount of the heat ΔQ_c (kcal/m²) removed from the unit surface area of the rolled material to a roll in the contact time is as follows:

$$\Delta Q_c=\int_0^t \lambda_1 \frac{\partial\theta}{\partial x}\bigg|_{x=0} dt=\frac{2\sqrt{t}\,\lambda_1(\theta_{01}-\theta_0)}{\sqrt{a_1\pi}} \qquad (3)$$

Consequently, the amount of the temperature drop $\Delta\theta_c$(°C) is calculated by the following formula:

$$\Delta\theta_c=\frac{2\Delta Q_c S}{\gamma c V} \qquad (4)$$

where, S : Contact surface area (m²),
V : Volume of strip element bitten in rolls (m³),
γ : Specific weight of strip (kg/m³),
c : Specific heat of strip (kcal/kg°C).

Here, the time t, the surface area S and the volume V, which are necessary to calculate $\Delta\theta_c$(°C) using equation (4), are given respectively as follows;

$$t=\frac{1}{\omega h_n \cos\phi_n}\left[(h_2+2R)\sin\phi_0-\frac{R}{2}(2\phi_0+\sin 2\phi_0)\right] \qquad (5)$$

$$S=RB\,\phi_0 \qquad (6)$$

$$V=RB(h_1\sin\phi_0+\frac{1}{2}R\sin 2\phi_0-R\phi_0) \qquad (7)$$

where, h_1 : Strip thickness at entrance of finisher (m),
h_2 : Strip thickness at exit (m),
ϕ_0 : Bite angle (rad),
ϕ_n : Neutral angle (rad),
ω : Angular velocity (rad/h),
h_n : Strip thickness at neutral point (m),
R : Roll radius (m),
B : Strip width (m).

2. 3 Temperature Rise by Friction Heat between Strip and Rolls

Friction heat is generated by the velocity difference between the strip and roll surfaces. Consequently, because of this, the temperature rises.

The friction work W_f (kg-m/m³) per unit volume of the strip during the contact time t is given by

$$W_f=\int_0^t wF dt \qquad (8)$$

Here, F indicates the area of the contact surface (m²) per unit volume. Assuming that the hatching part, as shown in Figure 1, is equivalent to the unit volume ($=1m^3$), the following relations are obtained:

$$Bhdx = BhRd\phi\cos\phi = 1 \qquad (9)$$

and

$$BRd\phi = F/2 \qquad (10)$$

From these, it follows that

$$F = 2/(h\cdot\cos\phi) \qquad (11)$$

where h is the strip thickness (m) at a given roll bite angle ϕ (rad).

w indicates the friction work (kg-m/m^2h) per unit time and unit surface area. It is presented as follows:

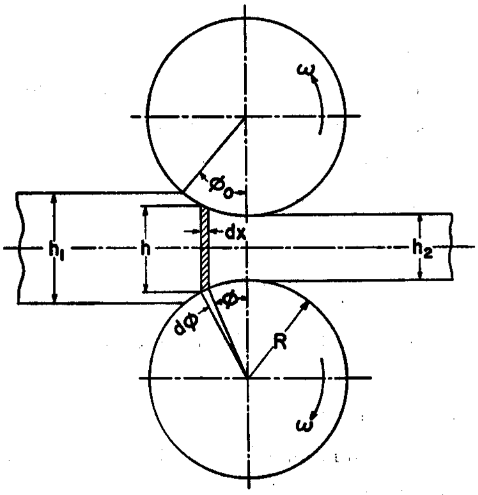

Figure 1 Schematic view of strip deformation in roll bite.

$$w = \mu p(\phi) v_r \qquad (12)$$

where, μ : Frictional coefficient,

v_r : Relative velocity (velocity difference between strip and roll surfaces, m/h),

$p(\phi)$: Roll pressure at a given roll bite angle ϕ.

Next, from the continuity equation the velocity of the strip element hatched in Fig. 1 becomes

$$\frac{dx}{dt} = \frac{h_n}{h} R\omega\cos\phi_n \qquad (13)$$

where, $dx = Rd\phi\cos\phi$, (14)

so that

$$dt = \frac{h\cos\phi}{h_n\omega\cos\phi_n}d\phi = \frac{\cos\phi[h_2+2R(1-\cos\phi)]}{h_n\omega\cos\phi_n}d\phi \qquad (15)$$

Equation (5), to calculate the contact time, is the result obtained by integrating equation (15).

Upon substituting equations (11), (12) and (15) into equation (8), we obtain

$$W_f = \int_{\phi_0}^{0} \frac{2\mu p(\phi) v_r}{h_n\omega\cos\phi_n}d\phi \qquad (16)$$

in which the relative velocity is qiven by

$$v_r = R\omega\left|1 - \frac{h_n\cos\phi_n}{h\cos\phi}\right| \qquad (17)$$

The amount of work calculated by equation (16) changes into the friction heat and it is distributed both to the strip and rolls. In a hot rolling, the temperature of the rolls is much lower than that of the strip. Therefore, the value of the heat conductivity of the rolls may be considered to be about twice as large as that of the strip. Consequently, the distribution ratio of the friction heat may be considered to be 60% to 70% for the rolls and 30% to 40% for the strip.

Finally, the temperature rise $\Delta\theta_f$(°C) of the strip by friction heat is approximately given by[5]

$$\Delta\theta_f = W_f A/(3\gamma c) \tag{18}$$

where, A indicates the heat equivalent of mechanical work.

2. 4 Temperature Rise by Plastic Deformation during Rolling

The amount of work W_p(kg-m/m³) generated by the plastic deformation per unit volume of the strip is commonly given as follows;

$$W_p = \int_0^{\varepsilon} k_f(\varepsilon_N)\, d\varepsilon \tag{19}$$

where, $k_f(\varepsilon_N)$ indicates the flow stress (kg/m²) of the strip. In the present study, the flow stress is assumed to be a function of the normal strain ε_N and the mean temperature θ_m(°C) in the thickness direction of the strip. It is given by

$$k_f = 1.15 \cdot 1.7 \cdot 10^6 \cdot \varepsilon_N^{0.2} \exp\left(\frac{2850}{\theta_m + 273}\right) \tag{20}$$

ε indicates the logarithmic strain, and is presented as

$$\varepsilon = \ln\frac{h}{h_2} = \ln\frac{h_2 + 2R(1-\cos\phi)}{h_2} \tag{21}$$

so that

$$d\varepsilon = \frac{2R\sin\phi}{h_2 + 2R(1-\cos\phi)}\, d\phi \tag{22}$$

From this, equation (19) is transformed to

$$W_p = \int_{\phi_0}^{0} \frac{2Rk_f \sin\phi}{h_2 + 2R(1-\cos\phi)}\, d\phi \tag{23}$$

Therefore, the temperature rise $\Delta\theta_p$(°C) of the strip by the plastic deformation may be calculated as

$$\Delta\theta_p = W_p A/(\gamma c) \tag{24}$$

As mentioned above, the calculation methods of the temperature drop $\Delta\theta_c$ by the heat conduction through the contact, the temperature rise $\Delta\theta_f$ by the friction heat and the temperature rise $\Delta\theta_p$ by the plastic deformation, have been indicated, respectively. The total amount of the temperature change $\Delta\theta$ of the strip during contact with the rolls is as follows:

$$\Delta\theta=\Delta\theta_p+\Delta\theta_f-\Delta\theta_c \tag{25}$$

Therefore, the strip temperature θ_2 at the exit of each finishing pass can be obtained by adding $\Delta\theta$ to the temperature θ_1 at the entrance:

$$\theta_2=\theta_1+\Delta\theta \tag{26}$$

Additionally, for the temperature change of the strip while moving on each stand interval, the radiation and the natural convection are taken into consideration. The calculation has been performed by the one-dimensional finite difference method, assuming that the heat transmission is in the direction of the strip thickness.

III. Assumptions and Conditions Adopted for Calculation, and Reduction Schedules in Finishing Process

In the present study, the finishing train is assumed to consist of six mills. The time descaling by water jet is 2. 5 seconds at the entrance of the first finisher. The coefficient α of the heat transfer between the water jet by the descaler and the strip surface is empirically valued at 1000 kcal/m²h°C. The temperature of the water and air is 25°C. The heat transfer coefficient by natural convection is used as $\alpha_n=7.2$ kcal/m²h°C. The value of the emissivity ε, which is necessary for the calculation of heat loss by radiation, is estimated invariably at 0. 58, considering the roughness of the strip surface.

The frictional coefficient, which is necessary to estimate the friction heat, is assumed to be 0. 3.

The rolled material is the killed steel containing 0. 08% carbon, and its specific weight γ is 7800 kg/m³. As the heat conductivity λ (kcal/mh°C) and the specific heat c (kcal/kg°C) differ depending upon the kind of steel and the temperature, the values indicated in the special report published by ISIJ[6] are used. (See Table 1).

The diameter of the finishing work roll is 680 mm from the first finisher to the sixth one, respectively. The initial temperature of each roll is assumed to be 50°C before contacting the strip. The heat conductivity and the specific heat for rolls are valued at this temperature: $\lambda_{02}=21.6$ kcal/mh°C and $c_{02}=0.128$ kcal/kg°C.

In this study, the rolling schedule in the finishing process is made for those cases where the strip is rolled from 25mm in bar thickness to 1. 2mm, 1. 6mm, 2. 0mm and 2. 5mm in final thickness. The entrance velocity of the strip at the first finisher is scheduled so that the exit velocity at the final finisher is 12m/s according to the usual

Table 1. Specific heat, thermal conductivity and thermal diffusivity used for temperature calculation of strip during rolling (0.08% carbon killed steel).

Temperature	Specific Heat	Thermal Conductivity	Thermal Diffusivity
θ (°C)	(kcal/kg°C)	(kcal/mh°C)	(m^2/h)
$1150>\theta\geq1100$	0.158	24.5	0.0199
$1100>\theta\geq1050$	0.158	24.1	0.0196
$1050>\theta\geq1000$	0.158	24.8	0.0201
$1000>\theta\geq950$	0.156	23.4	0.0192
$950>\theta\geq900$	0.156	23.0	0.0189
$900>\theta\geq850$	0.194	23.4	0.0155
$850>\theta\geq800$	0.206	24.5	0.0152
$800>\theta\geq750$	0.230	25.6	0.0143

operation. Therefore, the entrance velocity is changed by the final thickness, i. e., 0.576m/s, 0.768m/s, 0.960m/s and 1.20m/s for 1.2mm, 1.6mm, 2.0mm and 2.5mm in final thickness, respectively.

Next, we should consider the problem concerning the reduction schedule. However, not much data for the distribution of the reduction ratio at each pass in the finishing process can be found.

As for the roughing process, the problems about the reduction schedule were analytically discussed from the point of view of energy consumption and rolling capacity. These results were already reported[7].

For the case of the finishing process, there is merely an instance that the strip is rolled from 30mm in bar thickness to 3.2mm in final thickness through seven finishing passes[8]. According to this, the distribution of the reduction ratio is scheduled to decrease progressively from the earlier stage to the later stage. It is to be noted that the reduction ratio at the final finisher must be limited for controlling the profile and the flatness of the rolled products. The permissible reduction ratio is believed to be 20% at the highest.

Table 2, (a), (b) and (c), indicate three kinds of reduction schedules which are used in this calculation. In each part, the strip is scheduled to be reduced from 25 mm in bar thickness to the four kinds of final thickness (1.2mm, 1.6mm, 2.0mm and 2.5mm). The reduction schedules shown in Table 2 (a) and (b) are such that the reduction ratios are equally distributed from the first finisher F_1 to the fifth finisher F_5 and at 10% (a) and 20% (b) at the final finisher F_6. The reduction schedule in Table 2 (c) is such that the ratio is distributed so as to decrease according to the order from the earlier stage to the later one with an equal difference. Finally, it is set at 20%. Hereafter, the reduction schedule in (a), (b) and (c) will be called (a) type, (b) type and (c) type pass schedules, respectively.

Table 2. Strip thickness and reduction ratio for three types of pass schedules in the finishing process
((a) type, (b) type and (c) type pass schedules).

	Finishers		F_1	F_2	F_3	F_4	F_5	F_6
(a)	Strip thickness (mm)	25.0	13.9	7.7	4.3	2.4	1.3	1.2
	Reduction ratio (%)	—	44.4	44.4	44.4	44.4	44.4	10.0
	Strip thickness (mm)	25.0	14.7	8.7	5.1	3.0	1.8	1.6
	Reduction ratio (%)	—	41.1	41.1	41.1	41.1	41.1	10.0
	Strip thickness (mm)	25.0	15.4	9.5	5.8	3.6	2.2	2.0
	Reduction ratio (%)	—	38.4	38.4	38.4	38.4	38.4	10.0
	Strip thickness (mm)	25.0	16.1	10.4	6.7	4.3	2.8	2.5
	Reduction ratio (%)	—	35.6	35.6	35.6	35.6	35.6	10.0
	Finishers		F_1	F_2	F_3	F_4	F_5	F_6
(b)	Strip thickness (mm)	25.0	14.3	8.1	4.6	2.6	1.5	1.2
	Reduction ratio (%)	—	43.0	43.0	43.0	43.0	43.0	20.0
	Strip thickness (mm)	25.0	15.1	9.1	5.5	3.3	2.0	1.6
	Reduction ratio (%)	—	39.7	39.7	39.7	39.7	39.7	20.0
	Strip thickness (mm)	25.0	15.8	10.0	6.3	4.0	2.5	2.0
	Reduction ratio (%)	—	36.9	36.9	36.9	36.9	36.9	20.0
	Strip thickness (mm)	25.0	16.5	10.9	7.2	4.7	3.1	2.5
	Reduction ratio (%)	—	34.0	34.0	34.0	34.0	34.0	20.0
	Finishers		F_1	F_2	F_3	F_4	F_5	F_6
(c)	Strip thickness (mm)	25.0	10.6	5.3	3.1	2.0	1.5	1.2
	Reduction ratio (%)	—	57.8	49.8	41.8	33.8	25.8	20.0
	Strip thickness (mm)	25.0	12.4	6.8	4.2	2.8	2.0	1.6
	Reduction ratio (%)	—	50.6	44.8	39.0	33.2	27.4	20.0
	Strip thickness (mm)	25.0	13.2	7.6	4.9	3.4	2.5	2.0
	Reduction ratio (%)	—	47.4	41.9	36.4	31.0	25.5	20.0
	Strip thickness (mm)	25.0	14.3	8.8	5.8	4.1	3.1	2.5
	Reduction ratio (%)	—	42.9	38.3	33.6	29.2	24.5	20.0

IV. Calculation Results

4.1 Calculation Results for Change in Strip Temperature during Finishing

As mentioned above, it is important that the final rolling temperature be kept above the A_3 critical temperature. In this calculation, the A_3 critical temperature of the rolled material is assumed to be 830°C. Therefore, the temperature θ_F at the beginning of the descaling zone located before the first finisher F_1, which brings the

Table 3. Details of strip temperature drop for the three types of pass schedules in the case

Final thickness	Type	θ_F [°C]	DS	F_1			TL 1	F_2			TL 2	F_3		
				$\Delta\theta_p$	$\Delta\theta_f$	$\Delta\theta_c$		$\Delta\theta_p$	$\Delta\theta_f$	$\Delta\theta_c$		$\Delta\theta_p$	$\Delta\theta_f$	$\Delta\theta_c$
Final thickness = 1.2mm	(a)	1023	−40.1	15.6	3.8	37.5	−13.1	16.5	6.2	42.2	−11.3	17.5	10.8	47.2
				−18.1				−19.5				−18.9		
	(b)	1044	−40.5	14.2	3.3	37.8	−13.8	15.3	5.4	42.0	−11.8	16.3	9.1	46.9
				−20.3				−21.3				−21.5		
	(c)	1115	−44.1	20.5	7.7	46.3	−17.0	16.7	9.6	52.1	−14.4	15.3	10.7	55.3
				−18.1				−25.8				−29.3		
Final thickness = 2.5mm	(a)	942	−36.3	12.9	2.4	22.0	−5.3	12.6	3.2	23.5	−4.4	12.3	4.3	24.8
				−6.7				−7.7				−8.2		
	(b)	946	−36.6	12.1	2.1	21.6	−5.4	11.9	2.8	22.9	−4.5	11.5	3.7	24.0
				−7.4				−8.2				−8.8		
	(c)	959	−37.3	16.5	3.8	24.2	−6.0	14.1	4.2	26.3	−5.0	11.9	4.4	27.9
				−3.9				−8.0				−11.6		

final rolling temperature, has been numerically determined.

Table 3 indicates the calculation results for the case where the strip is rolled from 25mm in bar thickness to 1.2mm and 2.5mm in final thickness according to (a) type, (b) type and (c) type pass schedules, respectively. In this Table, the temperature rise $\Delta\theta_p$ by the plastic deformation, $\Delta\theta_f$ by the friction heat and the temperature drop $\Delta\theta_c$ by the heat conduction through the contact, are separately indicated. The total amount of the change in the strip temperature at each finishing mill is calculated by equation (25). As a result, the temperature of the strip during contact with the rolls decreases at each mill because the temperature drop $\Delta\theta_c$ by the contact heat loss is notably large. The drop in the strip temperature through radiation and convection is listed on each stand interval from **TL** 1 to **TL** 5. (**TL** 1: stand interval between F_1 and F_2.) The amount of the temperature drop for the case where the strip is rolled to 2.5mm in final thickness is found to be remarkably small in comparison with the case of 1.2mm. It is because the amount of the heat transferred from the strip to the surrounding atmosphere is approximately in proportion to the area of the strip surface.

Figure 2 (a), (b), (c) and (d) indicate the temperature process of the strip for each final thickness (1.2mm, 1.6mm, 2.0mm and 2.5mm) from the temperature at the beginning of the descaling zone before F_1 to θ_{F6}=830°C in the final rolling that the strip is rolled from 25 mm in bar thickness to 1.2 mm and 2.5 mm in final thickness.

TL 3	F_4			TL 4	F_5			TL 5	F_6			θ_{F6}
	$\Delta\theta_p$	$\Delta\theta_f$	$\Delta\theta_e$		$\Delta\theta_p$	$\Delta\theta_f$	$\Delta\theta_e$		$\Delta\theta_p$	$\Delta\theta_f$	$\Delta\theta_e$	[°C]
−10.0	17.6	19.5	51.1	−8.4	16.7	38.8	53.5	−8.2	2.1	1.0	36.1	830
		−14.0				+2.0				−33.0		
−10.7	17.3	16.9	52.0	−8.8	16.2	30.6	53.2	−8.5	5.3	4.9	43.2	830
		−17.8				−6.4				−33.0		
−12.3	10.8	10.4	55.3	−11.2	8.0	7.8	53.1	−8.5	5.3	4.9	43.2	830
		−34.1				−37.3				−33.0		
−4.0	12.0	5.9	26.2	−3.6	11.8	8.7	27.8	−3.4	2.1	0.6	19.8	830
		−8.3				−7.3				−17.1		
−4.0	11.2	4.9	25.1	−3.6	10.9	6.9	26.4	−3.4	5.2	2.4	24.0	830
		−9.0				−8.6				−16.4		
−4.5	9.3	4.0	27.1	−4.0	7.0	3.3	25.6	−3.4	5.2	2.4	24.0	830
		−13.8				−15.3				−16.4		

temperature. The temperature process is observed to differ in conformity with (a) type, (b) type and (c) type pass schedules for each final thickness.

The relation between the temperature θ_F and the final thickness for three kinds of pass schedules are calculated so that the final rolling temperature may be kept at $\theta_{F6}=830$°C. The results are indicated in Figure 3. From this, the influence of the pass schedule on the strip temperature θ_F at the entrance of the finishing train becomes conspicuous as the final thickness decreases. For the case of the hot coil of 2.5 mm in final thickness, the temperature difference of θ_F is a little less than 20°C, due to a change in (a) type and (c) type pass schedules, while for 1.2 mm the temperature differece is expanded above 90°C. In the case of finishing with (a) type and (b) type pass schedules, the temperature difference of θ_F increases with a decrease of the final thickness, although the difference is not considered to be serious. For the case of 1.2mm in final thickness, it is about 20°C. Finally, it may be concluded that the finishing with (a) type and (b) type among three kinds of pass schedules is comparatively effective for saving energy in the rolling process, because the reduction of θ_F results in that of the reheating temperature.

4.2 Calculation Results for Rolling Power and Rolling Force during Finishing

The calculations were performed by using Kármán's rolling equation to examine

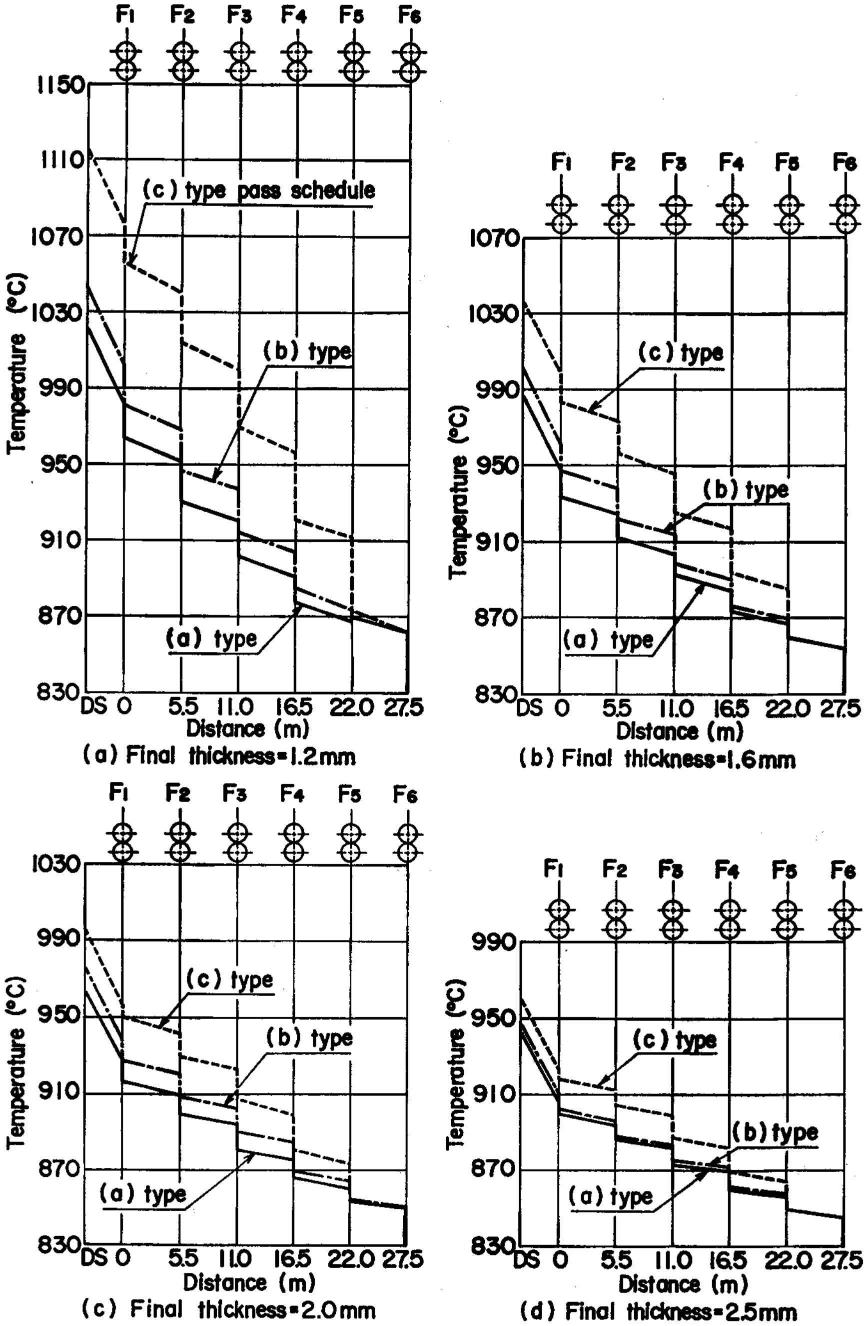

Figure 2 Comparison of temperature process due to change in pass schedule, so that the final temperature θ_{F6} may reach 830 °C.

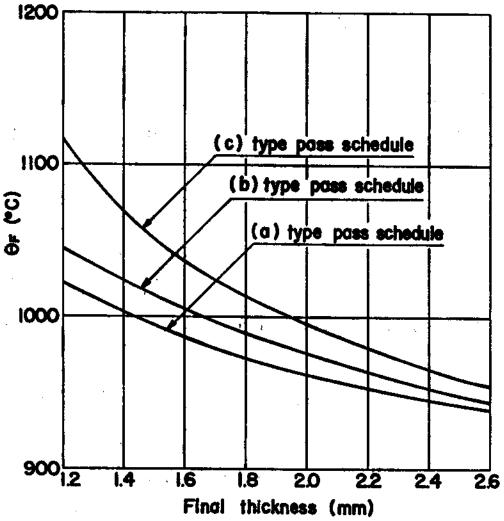

Figure 3 Relation between final thickness and temperature θ_F at the entrance of the finishing train in case of rolling with (a) type, (b) type and (c) type pass schedules.

how the rolling power and the rolling force are distributed at each finishing mill from F_1 to F_6 due to a change in the pass schedules ((a) type, (b) type and (c) type pass schedules).

Figure 4 (a), (b), (c) and (d) indicate the calculation results of the rolling power for each final thickness: 1.2mm (a), 1.6mm (b), 2.0mm (c) and 2.5 mm (d). Judging from this-figure, the rolling power in the case of the (c) type pass schedule decreases gradually from F_1 to F_5, although this pass schedule has been considered to be disadvantageous from the point of view of saving energy. No extreme

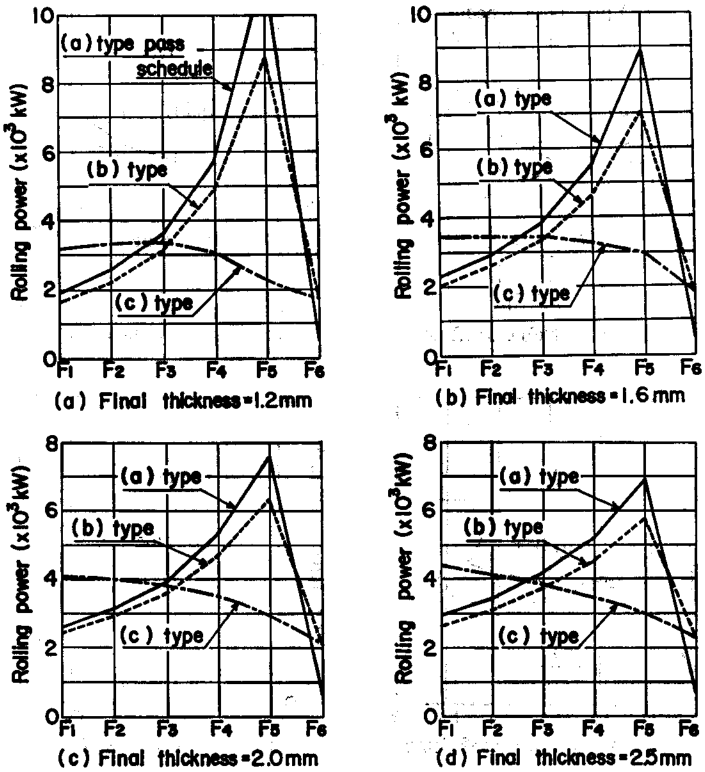

Figure 4 Comparison of rolling power due to change in pass schedule.

difference of the rolling power is found among six finishing mills. On the other hand, the rolling power in the case of the (a) type and (b) type pass schedules, which have been believed to be effective for saving energy, rises abruptly from F_1 to F_5, and falls extremely at the final finisher F_6. The distribution of the rolling power is unbalanced among the finishing mills. In particular, for a rolling to 1.2 mm in final thickness with the (a) type pass schedule, the rolling power at F_5 amounts to 11300 kW. For a rolling to 1.6mm, 2.0mm and 2.5mm in final thickness, the (a) type pass schedule brings an extremely high peak value at the fifth finisher F_5. This peak value in the rolling power becomes smaller to some degree with an increase of the final thickness.

Figure 5 (a), (b), (c) and (d) show the calculation results of the rolling force for each final thickness. It is evident from this figure that the rolling force in the case of the (c) type pass schedule decreases gradually from F_1 to F_6 as well as the rolling power. The rolling with the (a) type and (b) type pass schedules brings an acute rise in the rolling force at F_5 only for the case of 1.2mm in final thickness, and

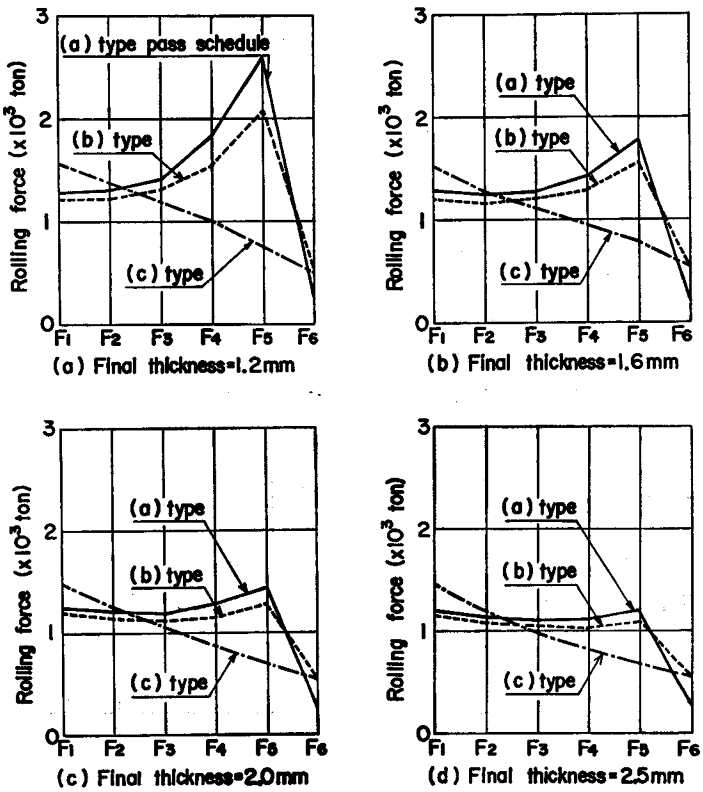

Figure 5 Comparison of rolling force due to change in pass schedule.

a comparatively flat distribution at each finisher from F_1 to F_5 for the case of 1.6mm, 2.0mm and 2.5mm.

V. Discussion

From the point of view of saving energy in the finishing process, the (a) type and (b) type pass schedules have been regarded as relatively advantageous in comparison with the (c) type pass schedule, when the strip is rolled to thin products from 1.2mm to 2.5mm in final thickness.

Illustrating by an example where a hot coil with 1.2 mm in final thickness is produced, the (a) type pass schedule is able to make the temperature θ_F at the entrance of the first finisher lower by 92°C than the (c) type. The reduction of the temperature θ_F results in that of the reheating temperature. Assuming that the amount of the temperature drop of the strip is constant in the process from the reheating furnace to the entrance of the finishing train, the reduction of 10°C in the temperature θ_F is equivalent to saving energy of 1580 kcal per ton of steel, because the specific heat c may be valued at 0.158 kcal/kg°C in this temperature range. However, the efficiency of the reheating furnace is not 100%. Usually, the actual efficiency is considered to range from 20% to 50%[9]. Therefore, the reduction of 10°C in θ_F should be considered to bring the saving energy of 3200 kcal to 7900 kcal per ton of steel, including the efficiency of the reheating furnace.

Consequently, the (c) type pass schedule, where the reduction ratio decreases while progressing from the first finisher F_1 to the final one F_6, should be reconsidered from a standpoint of the energy consumption in the rolling process, in particular for producing thin hot coils. On the other hand, the application of the (a) type or (b) type pass schedule to the actual rolling operation is difficult, even though such pass schedules have an advantage in saving energy. This is because the distribution of the rolling power and the rolling force is unbalanced among the six finishers and has an extremely high peak value, as indicated in Fig. 4 and Fig. 5. With a decrease of the final thickness its tendency becomes remarkable.

Recently, with the developments and improvements of the lubricants for a hot strip mill[10], the lubricants have been often applied to the finishing rolls. It has an effect on the decrease of the rolling power and the rolling force. At the same time, it contributes to the elongation of the roll life because of the smooth contact between the strip and the roll surfaces.

Therefore, it has been demonstratively examined how the decrease of the friction coefficient by applying the lubricants has an effect on the rolling power and the rolling force.

Figure 6 (A), (B) and (C) indicate the calculation results for the case of producing

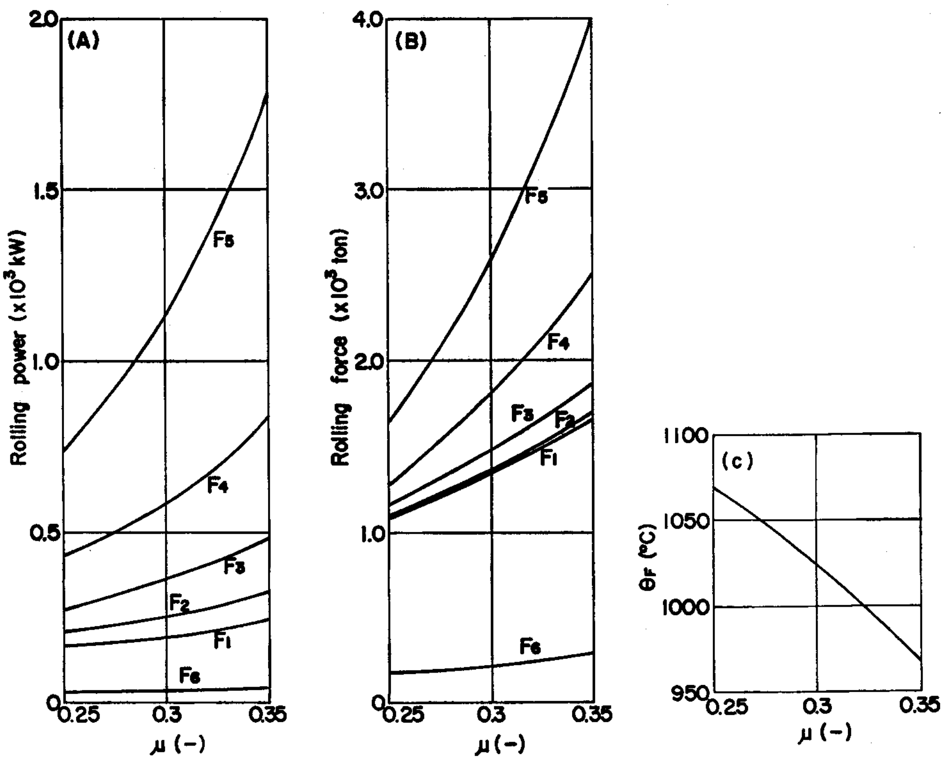

Figure 6 Influence of friction coefficient μ on rolling power (A), rolling force (B) and temperature θ_F (C) in case of rolling from 25 mm to 1.2 mm with (a) type pass schedule.

hot coils with 1.2mm in final thickness using the (a) type pass schedule. Figs (A) and (B) show the rolling power and the rolling force at each finishing mill in the range of the friction coefficient μ from 0.25 to 0.35. Fig (C) shows the temperature θ_F at the entrance of the finishing train which is required to rise to 830°C at the exit of the final finisher. It is obvious from these figures that both the rolling power and the rolling force decrease with a decrease of the friction coefficient. The decreasing rate of both is seen to be remarkable at the finishers F_4 and F_5. On the contrary, θ_F required to rise to 830°C at the exit of the final finisher, increases with a decrease of the friction coefficient because of the reduction of the friction heat generated by the velocity difference between the strip and the roll surfaces. The temperature θ_F amounts to 1069°C, assuming that the friction coefficient μ is reduced from 0.3 to 0.25, while θ_F is 1023°C in the case of μ=0.3, as indicated in Table 3. The difference of θ_F results in 46°C between both. However, the difference is considered to become smaller, when the lubricants are applied only to the finishers F_4 and F_5, where the rolling power and the rolling force have a peak value. At the same time, the distributions of the rolling power and the rolling force are obviously uniform in comparison with the case indicated in Fig. 4 and Fig. 5.

Although we can not generalize from only three types of pass schedules, a pass schedule which is similar to the (a) type and (b) type pass schedules may be concluded to have an effect on saving energy in the finishing process. Furthermore, it may be possible to put such type pass schedules to practical use according to the countermeasure.

VI. Conclusions

The main purpose of this paper is to find out a pass schedule in the finishing process whereby the energy consumption may be reduced to a minimum. Here, three kinds of pass schedules have been used: an equal reduction ratio from the first finisher F_1 to the fifth one F_5 and 10% at the final finisher F_6 ((a) type pass schedule), 20% at F_6 ((b) type), and a reduction ratio decreased with equal difference while progressing from F_1 to F_6 ((c) type).

In this paper, it was first discussed how the strip temperature drops owing to a change in the reduction schedule using a mathematical modelling whereby the strip is rolled from 25mm in bar thickness to 1.2mm, 1.6mm, 2.0mm and 2.5mm in final thickness through six passes finishing. At the same time, problems concerning the rolling power and the rolling force at each finishing mill were analytically examined. Secondly, the degree of the influence of the friction coefficient on the change in the strip temperature was numerically examined, assuming that the friction coefficient between the strip and rolls surfaces had been reduced by applying lubricants.

The results obtained in this study may be summarized as follows:

1) The influence of the change in the pass schedule on the temperature θ_F at the entrance of the finishing train has been found not to be negligible through a decrease of the final thickness. Illustrating by an example where a hot coil with 1.2 mm in final thickness is produced, the (a) type pass schedule enables the temperature θ_F to become lower by 92°C than the (c) type pass schedule. This may be considered to be effective for saving energy in the rolling process. The (b) type pass schedule has been found to be comparable to the (a) type pass schedule as regards influence on the temperature θ_F.

2) The rolling power and the rolling force decrease gradually from F_1 to F_6 in the case of finishing with the (c) type pass schedule. On the other hand, a rolling with the (a) type and (b) type pass schedules brings an acute rise both in the rolling power and the rolling force when progressing from F_1 to F_5. Its tendency becomes remarkable with a decrease of the final thickness.

3) In the case of a rolling with the (a) type and (b) type pass schedules, which

are effective for saving energy, the distribution of both the rolling power and the rolling force among six finishers has been found to be flat to some extent by applying lubricants at F_4 and F_5, where both have an extremely high peak value.

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