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Integrated On-line Model for the Prediction of Roll Force and Temperature in Thick Plate Rolling

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ABSTRACT

An integrated mathematical model which links microstructural evolution of plain carbon steels has been developed to predict the roll force and temperature during heavy plate rolling. It consists of submodels for deformation resistance considered recrystallisation, and average and surface temperature devided with cooling zones as like as descaling, water running, air contact and rolling. Also, for a geometrical resistance during rolling, a series of thick plate rolling conditions were used for finite element simulation of rolling process, with different variations of roll radius, rolling ratio, and matching for the different dimensions of the products. The prediction accuracy of the proposed on-line model was examined through comparision with many data of measured mill load and surface temperature.

Key words : Roll force; Temperature; On-line model; Heavy plate rolling

1. INTRODUCTION

In industrial rolling process, the thickness of the rolled plate is required to be as close as possible to the target value. Also, an unloaded roll gap is always different from rolled thickness due to the elastic deformation of mill housing. Therefore, when the elastic strech of mill can be evaluated, an accurate prediction of roll force and temperature is crucial for achievement of the target thickness. The roll force is affected by process parameters such as plate geometry, reduction ratio, temperature and mechanical properties of plates and roll.

In this paper, an integrated mathematical model which links microstructural evolution of plain carbon steels has been developed to predict the roll force and temperature during heavy plate rolling. It consists of submodels for deformation resistance considered recrystallisation, and average and surface temperature devided with cooling zones as like as descaling, water running, air contact and rolling. Also, for a geometrical resistance during rolling, a series of thick plate rolling conditions were used for finite element simulation of rolling process, with different variations of roll radius, rolling ratio, and matching for the different dimensions of the products. The prediction accuracy of the proposed on-line model was examined through comparision with many data of measured mill load and surface temperature.

2. ROLL FORCE MODEL

Accoding to classical theories of rolling process, the roll force can be expressed as deformation resistance of rolled material and

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geometrical resistance decided by rolling conditions. The most widely used and effective roll force model is based on conventional theory by Sims[1], as following,

$$F = WQ_pK_ml_d \qquad (1)$$

where F, W, Q_p and l_d denote the roll force, plate width, geometrical resistance and contact length between roll and plate, respectively.

In POSCO's heavy plate mill, the deformation and geometrical resistance are taken into account by mixture resistance as it is called material hardness. The material hardness is applied as proportionality factor between the reduction ratio and roll force.

The results compared with Sims and hardness model are shown in table 1.

Although the hardness model is more simple than Sims model and fastly runs during on-line calculation, its physical meaning is not as clear as Sims model. Also, the effects for deformation resistance of chemical components are only considered as equivalent carbon in temperature correction factor C_T. The structure of Sims model has an integrated form with definitely physical meaning and easy application to new material.

Therefore, for the prediction of roll force, a Sims' type of equation (1) is employed in this paper. But, on-line results of Sims model do not work as best as expected because of geomtrical resistance with constant friction coefficient and peening effect[2] ; In the case of heavy-gauge plates, the undeformed part of material enters the roll gap and increases roll force.

To predict the geometrical resistance, Hwang[3] was proposed the hypothetical mode of hot strip rolling; each segment of the strip is uniaxially compressed from entry to exit thickness, while passing through the bite region and no friction is present at the strip-roll interface.

2.1 Geometrical resistance

In this paper, the hypothetical mode of Hwang is used and the hypothetical roll force for heavy plate rolling can be calculated as follows,

$$F_m = WK_mR\cos\theta \qquad (2)$$

where K_m and θ denote the mean deformation resistance in bite region and contact angle, respectively.

A finite element model employed for the present investigation consists of two parts; a part for the analysis of steady state thermo-viscoplastic deformation and temperature of the plate and a part for that of steady state heat

Table 1. Comparision between Sims and hardness model

Index	Sims model	Hardness model
Roll force	$F = WQ_pK_ml_d$	$F = H_mrZ$
Flattening effect of work roll	flattened radius(R') $l_d = \sqrt{R'rH}$	$Z(K_{ref}, C_T, H)$
Deformation resistance	$Km = f(\varepsilon, \varepsilon LT)$	$H_m = K_{ref}WC_TC_hC_VR/R_{ref}$ $C_T = a_1\exp[C_{eq}(1-(T/T_{ref})^2]$ $C_h = a_2 + a_3H + a_4H^2 + a_5H^3$ $C_v = a_6 + a_7V$
Geometrical resistance	$Q_p = g(r, R', H)$ $= b_1 + (b_2 + b_3r)\left[\sqrt{\frac{R'}{H}} - b_4\right]$	
Where K_{ref}, r, H, ε, ε and T are reference strength, reduction ratio, entry thickness, strain, strain rate and temperature. Also, C_{eq}, R and V are equivalent carbon, unflattened radius and rolling speed. * 'ref' denote a reference value.		

transfer in the work roll. A series of finite element process simulation is conducted with each set of the perturbable process parameters such as shape factor s, reduction ratio r, friction coefficient μ, roll radius R, rolling speed V, entry mean temperature T_{entry} and equivalent carbon contents C_{eq}.

From results of parameter analysis as shown in figure 1, there is no difference of Q_p with the change of roll radius, rolling speed, entry mean temperature and equivalent carbon contents.

Then, the geometical resistance can be defined as the ratio of roll force obtained by simulation results to the hypothetical roll force, as follows,

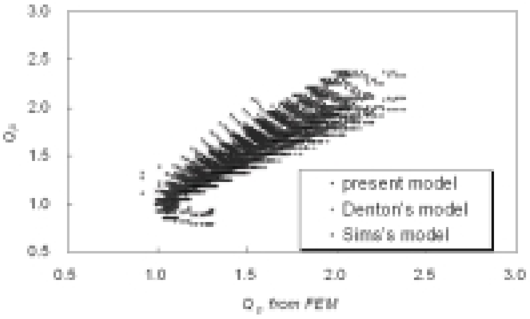


Fig. 2 Comparision between values of geometrical resistance Qp predicted from equation(3) and that predicted from finite element simulation. (where, the misaka's model is used for calculation of deformation resistance.) Also, shown are the comparision with Denton[4] and Sims.

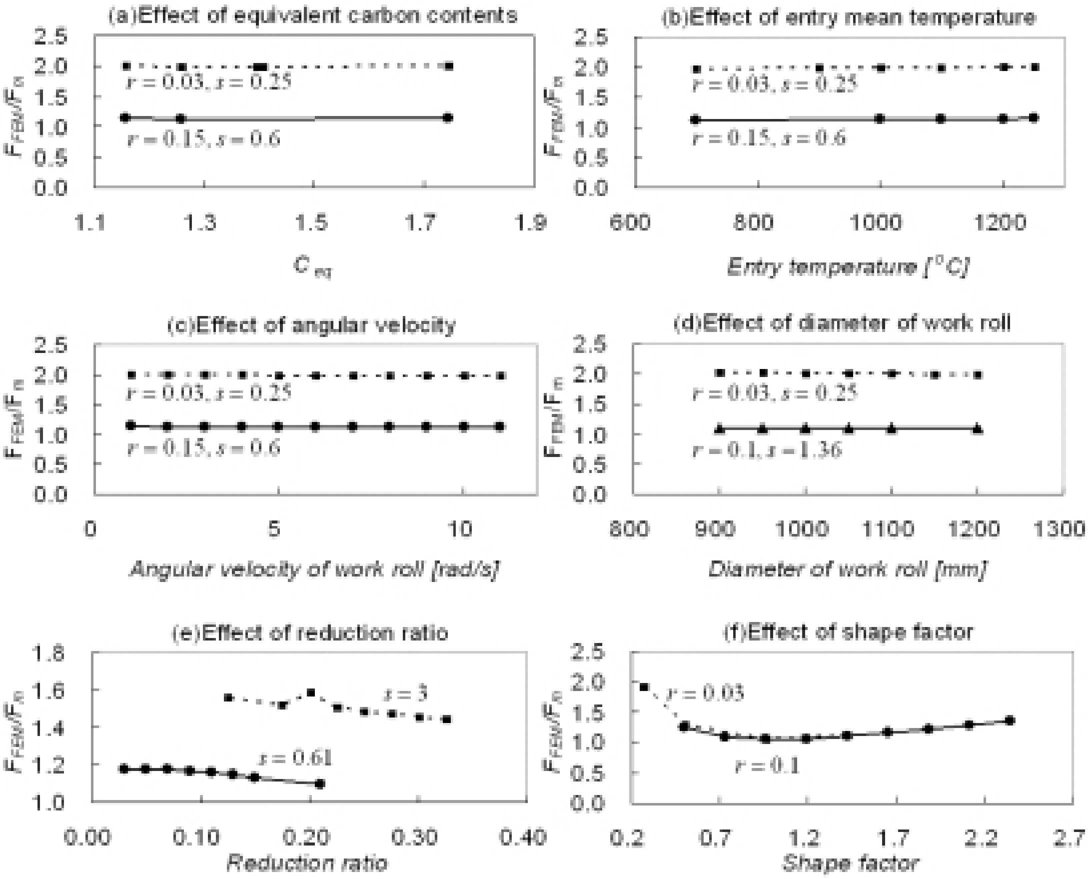


Fig. 1 Effect of various rolling parameters on the geometrical resistance. F_{FEM} is the roll force given by finite element analysis and F_m means hypothetical roll force.

$$Q_p = F/F_m = f(s, r, \mu) = c_1 s^2 + (c_2 + c_3\mu + c_4 \ln r)s + c_5 \ln s + c_6 \ln r + c_7 r^2 + c_8 r + c_9 \qquad (3)$$

2.2 Deformation resistance

The deformation resistance of plain carbon steels is as follows,

$$K_m = \frac{2}{\sqrt{3}\varepsilon}\int_{\varepsilon_a}^{\varepsilon+\varepsilon_a} \sigma(\%C, \%Mn, ..., \%Nb, \varepsilon, \varepsilon LT)d\varepsilon$$
$$= \frac{2}{\sqrt{3}}\sigma_m(\%C, \%Mn, ..., \%Nb, \varepsilon_m, \varepsilon_m, \varepsilon_a, T) \qquad (4)$$

where ‘m’ means the average value in bite region and σ_m denotes mean flow stress in bite region.

As shown in equation (5), the updated Misaka’s equation for the multiply alloyed steels by Kang[5] is used to specify the reference flow stress and the terms of retained strain ε_a and steel composition (%C, %Mn, ..., %Nb) are employed to minimize the error for on-line roll force of reference flow stress.

$$\sigma_m = \sigma_m(C_{eq}, \sigma_{misaka}, \varepsilon_m, \varepsilon_m, \varepsilon_a, T)$$
$$= \sigma_{misaka}^k \varepsilon_m^p \varepsilon_m^n \left(\frac{\varepsilon_m + \varepsilon_a}{\varepsilon_m}\right)^l \exp\left(C_{eq} + \frac{Q}{T+273}\right) \qquad (5)$$

where

$$\sigma_{misaka} = f\varepsilon_m^{0.21}\varepsilon_m^{0.13}\exp(0.126 - 1.75\%C + 0.594\%C^2$$
$$\frac{2851 + 2968\%C - 1120\%C^2}{T+273})$$
$$f = 0.963 + 0.161Mn + 4.388Nb + 0.86V + 4.03Ti + 0.29Mo + 0.022Ni + 0.028Cr$$
$$\varepsilon_m = \frac{4}{\sqrt{3}}\left(1 - \frac{\tan^{-1}\delta}{\delta}\right), \delta = \sqrt{\frac{r}{1-r}},$$
$$\varepsilon_m = \frac{2V}{\sqrt{3}l_d}\ln\left(\frac{1}{1-r}\right)$$

Also k, p, n, l, C_{eq} and Q are adjusted by regression analysis for the logarithmic equation of actual deformation resistance derived from measured roll force.

$$\ln\left(\sigma_{actual} \cong \frac{\sqrt{3}}{2}\frac{F_{actual}}{WQ_p l_d}\right) = k\ln\sigma_{misaka} + p\ln\varepsilon_m$$
$$+ n\ln\varepsilon_m + l\ln\left(\frac{\varepsilon_m + \varepsilon_a}{\varepsilon_m}\right) + C_{eq} + \frac{Q}{T+273}$$

2.3 Retained strain

The plate in heavy plate rolling generally undergoes the microstructural changes due to re-crystallisation, grain growth and precipitation. When a partial recrystallization occurs in interpass time, a certain fraction of strain will be accumulated as equation (6). This strain plays an important role in increasing the deformation resistance of next pass.

$$\varepsilon_a = 0.5\varepsilon(1 - X) \qquad (6)$$

where X is the recrystallized volume fraction and is calculated using microstructural equations by Sellas[6], Singh[7] and Lenard[8].

3. TEMPERATURE MODEL

After the slab is extracted from furnace, its mean temperature defined as a representative value over the plate length and thickness, is gradually decreased by heat transfer phenomena such as loss to the environment, loss to the rolls and heat generation from plastic deformation of plate. Then, the mean temperature control of plate plays an important role in calculation of roll force, microstructure and draft schedule.

The mean temperature model generally used in on-line process of heavy plate mill is as follows,

$$T(i+1) = T(i) + \Delta T_{deformation} - \Delta T_{contact} - \Delta T_{air} - \Delta T_{discaling} \qquad (7)$$

where $T(i)$ is the mean temperature at entry thickness of i-th rolling pass and $\Delta T_{deformation}$, $\Delta T_{contact}$, ΔT_{air} and $\Delta T_{descaling}$ are a temperature rise due to plastic deformation, a temperature loss due to roll / plate contact, environment air and descaling process.

3.1 Rolling section

As shown in Figure 3, mean temperature of exit thickness can be calculated by considering all heat transfer phenomena in bite angle; heat generation due to plastic deformation of plate and friction between plate and work roll, and contact heat loss from plate to roll at contact length.

The total energy input per unit time and width is given by and the total energy output is given by $P_{\text{out}} = P_2 + 2Q_{contact}$.

From the energy balance principle, $P_{in} = P_{out}$.

Therefore,

$$\Delta T_{rolling} = \Delta T_{contact} - \Delta T_{deformation} = T(i) - \frac{P_1 + 2Q_{friction} - 2Q_{contact} + Q_{deformation}}{\rho C_p V_{exit} H_{exit}} \tag{8}$$

where ρ and C_p are plate density and heat capacitance.

According to hypothetical mode [9]for P^{h}_{m} and $Q^{\text{h}}_{\text{contact}}$, and FE based parameter analysis just as that of geometrical resistance of roll force F for plate rolling conditions, all models such as roll power P, forward slip f_s, firction energy $Q_{friction}$, contact heat loss energy $Q_{contact}$, deformation heat generation energy $Q_{deformation}$ are developed, as follows.

- Rolling power : $P = Q_{deformation} + 4Q_{friction} = z_1(s, r, \mu)P^h_m$
- Hypothetical rolling power :

$$P^h_m = \frac{V_{exit} H_{exit} F}{W l_d} \ln\left(\frac{H_{entry}}{H_{exit}}\right)$$

- Hypothetical maximum contact heat energy : $Q^h_{contact} = H_{entry} T_{entry} l_d$
- Forward slip : $f_s = \dfrac{V_{exit} - V}{V} z_2(s, r, \mu)$
- Assumption for friction heat energy : $Q_{friction} / Q_{deformation} = z_3(s, r, \mu)$
- Ratio of deformation energy to hypothetical rolling power : $Q_{deformation} / P^h_m = z_1(1 + 4z_3)$
- Ratio of contact energy to maximum contact heat energy : $Q_{contact} / Q^h_{contant} = z_4(s, r, \omega, h_{\text{lub}})$

where h_{lub} and ω are contact heat transfer coefficient and angular velocity of roll.

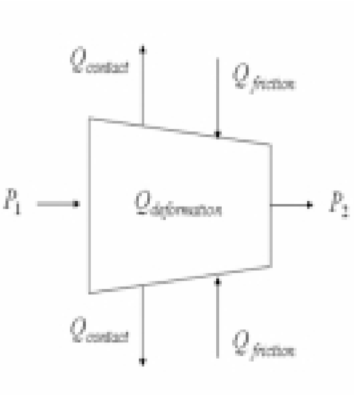
Heat transfer phenomena		Expressions
	Heat energy input rate due to incoming plate	$P_1 = H_{entry} V_{entry} \int_0^{T_{entry}} \rho C_p dT \cong \rho C_p H_{exit} V_{exit} T_{entry}$
	Heat generation due to friction	$Q_{friction} = \frac{1}{2} \int_0^{\theta} \lvert \tau (V_{plate} - V) \rvert R' d\phi$ Where τ is frictional stress.
	Heat generation due to plastic deformation	$Q_{deformation} = \int_{\Omega} \bar{\sigma} \dot{\bar{\varepsilon}} d\Omega$
	Heat energy input rate due to incoming plate	$P_2 = \rho C_p H_{exit} V_{exit} T_{exit}$
	Heat loss from plate to roll due to contact	$Q_{contact} = \int_{contact} h_{lub} (T_{plate} - T_{roll}) dT$

Fig. 3 Energy balance of plate in rolling section

Finally, the mean temperature of exit thickness is,

$$T_{exit} = T(i) - \Delta T_{rolling} = T(i) + \frac{z_1(1+2z_3)}{1+4z_3}\frac{Q_p F_m}{\rho C_p W l_d} \ln\left(\frac{H_{entry}}{H_{exit}}\right) - \frac{2z_4 h_{\mathrm{lub}} T(i) l_d}{\rho C_p H_{exit} V(1+z_2)} \qquad (9)$$

3.2 Non-rolling section

During the interpass or delivery time, mean temperature can be calculated by considering heat transfer boundary conditions such as radiation and convection.

In the present investigation, the reference temperature based on exit mean temperature is modeled as follows,

$$T_{ref} = T_{exit} - \Delta T_{radiation} - \Delta T_{convection} \qquad (10)$$

where

$$\Delta T_{radiation} = T_{exit} + 273 - \left[(T_{exit}+273)^{-3} + \frac{3\sigma(\varepsilon_u + \varepsilon_d)}{\rho C_p H_{exit}} t\right]^{-3}$$

$$\Delta T_{convection} = (T_{exit} - T_{environment})\left[1 - \exp\left(-\frac{h_u + h_d}{\rho C_p H_{exit}} t\right)\right]$$

and subscript ‘u’ and ‘d’ mean the upper and lower surface of plate.

But, the reference temperature of equation (10) has an error because heat loss phenomena occur at the upper and lower surface and must be calculated using surface values at those surfaces.

Therefore, according to parameter analysis of rolling conditions and FE based model for non-steady state heat transfer analysis, final temperature drop in non-rolling region can be calculated as follows.

- descaling process : emissivity $\varepsilon_u = \varepsilon_d = 0$ and $T_{environment} = T_w$

$$T(i+1) = T_w + (T_{ref} - T_w)$$

$$f\left(\frac{kt}{\rho C_p H_{exit}^2}, \frac{h_w H_{exit}}{k}, \frac{H_{exit}}{H_{ref}}, \frac{T_{ref} - T_w}{T_{exit} - T_w}\right)$$

- running water process : emissivity $\varepsilon_u = 0$ and $T_u = T_w$, $T_d = T_{air}$

$T(\mathrm{i} + 1) = T_{ref}$

- air cooling : $T_{environment} = T_{air}$

$$T(i+1) = T_{air} + (T_{ref} - T_{air})$$

$$f\left(\frac{kt}{\rho C_p H_{exit}^2}, \frac{h_w H_{exit}}{k}, \varepsilon_u, \varepsilon_d, \frac{H_{exit}}{H_{ref}}, \frac{T_{ref} - T_{air}}{T_{exit} - T_{air}}\right)$$

where k is the conductivity of plate.

3.3 Surface temperature

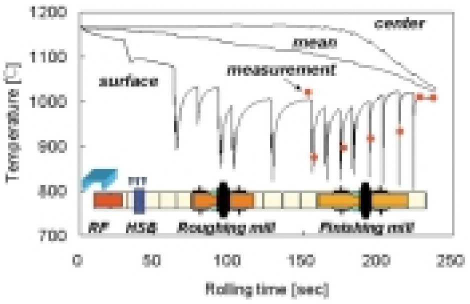
On the assumption that heat transfer is only considered in the plate thickness, the surface temperature can be computed using finite difference method with boundary conditions considering the frcition energy, contact heat energy and plastic heat generation. Then, heat transfer co-efficients such as h_u, h_d, ε_u and ε_d are established by comparision with calculated temperature and mesured values at acutal mill line.

4. RESULTS AND DISCUSSION

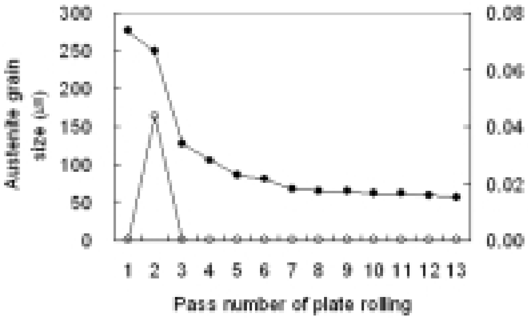
Figure 4 shows the evolution of temperature distribution and retained strain of plane carbon steel during the heavy plate rolling. The problem investigated is a rolling condition for a plate with variation of thickness from 250mm slab to 31.73mm during 13 rolling passes.

It may be observed from the figure 4(a) that the mean temperature is gradually decreased after the slab is extracted from furnace. But, center temperature has a little increase in rolling section by deformation energy and friction with roll. Also, the calculated surface temperature is basically in good agreement with the measured values and is affected by the boundary conditions such as descaling, water running, rolling and air cooling.

As shown in figure 4(b), the effect of rescrystallization and retained strain accumulated from 2-pass is taken into account in the calculation of roll force of 3-pass.



(a) temperature distribution during the heavy plate rolling



(b) variations of austenite grain size and reatined strain during the heavy plate rolling.

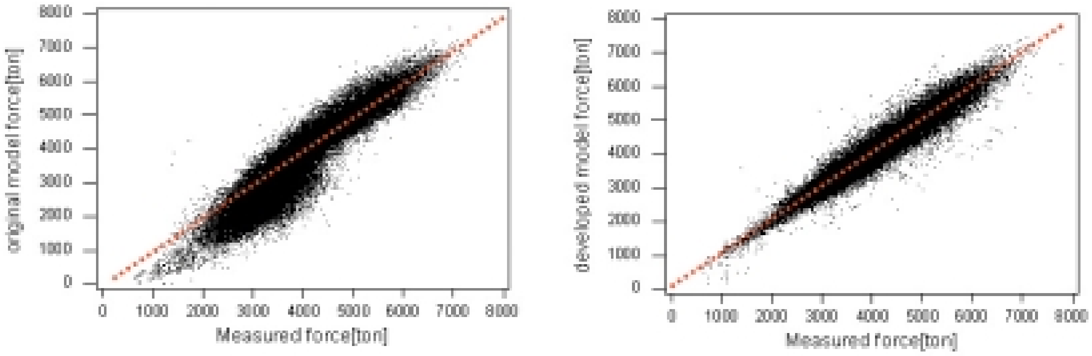
Fig. 4 Evolution of (a) temperature distribution and (b) austenite grain size and reatined strain during the heavy plate rolling

In order to study the accuracy comparison of roll force models, the developed model is tested by selecting two 40000-actual data sets. In the first step of the developmet, the temperature field and retained strain are calculated with an acutal data set. In the second step, the deformation resistance of equation (5) is calculated considering given temperature and strain. In the third step, the roll force model is retested using another actual data set. As shown in figure 5, the standard deviation of shooting rate on measured roll force is greatly decreased from 14.8% to 5.8%.

5. CONCLUSIONS

Presented in this paper is an integrated mathematical model which links microstructural evolution of plain carbon steels to predict the roll force and temperature during heavy plate rolling.

A main merit of the present approach may be found in the rigorous treatment of, for example, the geometrical resistance based on hypothetical mode and finite element method, the deformation resistance considering recrystallisation and chemical compositions and



(a) hardness model

(b) developed roll force

Fig. 5 Comparison between the values of roll force model and measured roll foce. A dotted line means the no error line between the models and measered values.

The mean temperature and surface models devided with cooling zones as like as descaling, water running, air contact and rolling.

Consequently, the actual roll force in plate mill could be predicted with good acccuracy. Further, the present approach may be successfully applied to the accurate roll gap set-up.

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