FE-based On-line Model for the Prediction of Roll Force and Roll Power in Hot Strip Rolling

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Investigated via a series of finite element process simulation is the effect of diverse process variables on some selected non-dimensional parameters characterizing the thermo-mechanical behavior of the strip in hot strip rolling. Then, on the basis of these parameters an on-line model is derived for the precise prediction of roll force and roll power. The prediction accuracy of the proposed model is examined through comparison with predictions from a finite element process model.

KEY WORDS: hot strip rolling; roll force; roll power; on-line model; finite element process model.

1. Introduction

In hot strip rolling, a capability for precisely predicting roll force and roll power is crucial for sound process control. In the past, on-line prediction models have been developed mostly on the basis of Orowan’s theory1) and its variations.2–4) However, the range of process conditions in which desired prediction accuracy could be achieved was rather limited, mainly due to many simplifying assumptions inherent to Orowan’s theory. As far as the prediction accuracy is concerned, a rigorously formulated finite element (FE) process model is perhaps the best choice. However, a FE process model in general requires a large CPU time, rendering itself inadequate for on-line purpose.

In this paper, we present a FE-based on-line prediction model applicable to precision process control in a finishing mill. Described was an integrated FE process model capable of revealing the detailed aspects of the thermo-mechanical behavior of the roll–strip system. Using the FE process model, a series of process simulation was conducted to investigate the effect of diverse process variables on some selected non-dimensional parameters characterizing the thermo-mechanical behavior of the strip. Then, it was shown that an on-line model for the prediction of roll force and roll power could be derived on the basis of these parameters. The prediction accuracy of the proposed model was examined through comparison with predictions from the FE process model.

2. An Integrated FE Process Model

An integrated FE process model employed for the present investigation consists of three basic FE models: a model for the analysis of steady-state thermo-viscoplastic deformation of the strip, a model for the analysis of steady-state heat transfer in the strip, and a model for the analysis of steady-state heat transfer in the work roll. As shown in Fig. 1, interaction between the thermal behavior of the work roll and that of the strip due to roll-strip contact as well as interaction between the thermal behavior of the strip and the mechanical behavior of the strip were taken into account by iterative solution schemes. The thermal and mechanical boundary conditions adopted for the basic FE models were summarized in Fig. 2. More details regarding the process model and its solution accuracy may be found in the reference.5) It was assumed that the work roll was rigid and the strip deformed under the plane-strain conditi-

Fig. 1. An integrated finite element process model for the analysis of the thermo-mechanical behavior of the roll–strip system in hot strip rolling.
3. Hypothetical Mode of Rolling

Suppose that, in actual rolling, the thickness of a strip (inlet temperature $T_1$, flow stress $\sigma$, ...) is reduced from $H_1$ to $H_2$, with its exit speed and exit temperature being $V_2$ and $T_2$, respectively. Now, for the same rolling geometry and the same strip, consider an hypothetical mode of rolling in which each segment of the strip is uniaxially compressed from $H_1$ to $H_2$, while passing through the bite region and no friction is present at the roll-strip interface, as shown in Fig. 3. Further, the strip temperatures in the bite region are uniform along the thickness direction and vary linearly along the rolling direction, such that the inlet and exit temperature coincide with $T_1$ and $T_2$, respectively. Also, assume that the exit speed is equal to $V_2$. Then, $P'$: the deformation energy rate associated with the hypothetical mode, may be approximated by

$$P' = V_2 H_2 E' \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots$$

$$E' = \int \sigma \tilde{e} \, dh \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cd ..
suggested that the most favorable combination of $r$ and $s$ in terms of the roll power efficiency is $r = 0.3$ and $s = 1–2$, when $\mu$ is greater than 0.3.

Illustrated in Fig. 6 was the complex nature of the effect of $\mu$, $s$, and $r$ on forward slip, which may be described as follows. When $r$ was smaller than 0.1, the effect of $\mu$ on forward slip was not significant, as may be seen from Fig. 6(a). When $r$ was greater than 0.3, forward slip was increased as $\mu$ was increased for any given values of $s$ and $r$, as shown in Fig. 6(b). Also, forward slip was decreased as $s$ was increased for any given values of $\mu$ ($>0.3$) and $r$, provided $r$ was smaller than 0.3. However, the trend was reversed when $r$ was greater than 0.4, namely, forward slip was increased as $s$ was increased for any given values of $\mu$ and $r$. It was also found that forward slip was increased as $r$ was increased for any given values of $\mu$ and $s$, provided $s$ was greater than 3. However, when $s$ was smaller than 3, the trend was valid only until $r$ reached 0.3.

Figure 7(a) shows how the torque factor varied with $s$ and $r$, when $\mu = 0.3$. It may be observed from the figure that the torque factor was increased as $r$ was increased for a given value of $s$, while for a given value of $r$, the torque factor was decreased as $s$ was increased. As far as the effect of $\mu$ was concerned, it was revealed that the torque factor was insensitive to $\mu$, as shown in Fig. 7(b), indicating that the curves shown in Fig. 7(a) could be applied regardless of the $\mu$ value.

5. On-line Model

A series of FE process simulation was also conducted with each of the perturbed sets—a reference set of process conditions is perturbed in terms of at least one of the following process variables: flow stress characteristics of the strip material, $R$, $\omega$, $T_1$, thermal properties of the roll material, and heat transfer coefficient at the roll–strip interface ($h_{bs}$). The perturbed sets were described in Table 1. It was
revealed that the aforementioned non-dimensional parameters were little affected by the perturbation of these process variables, which was partly illustrated in Fig. 8. This enabled us to develop an on-line model for the prediction of forward slip, roll power, and roll force, as follows:

\[
\begin{align*}
\frac{P}{r^2} &= 0.048914 - 0.020905 \rho + 0.62861 r - 0.065703 s + 0.031745 \eta^2 + 0.68811 \eta r, \\
&\quad -1.715 \eta^2 + 0.03135 \rho - 0.24130 r + 0.0009791 \eta - 0.8775 \rho \eta + 4.4139 \eta^2, \\
&\quad -0.6325 \eta^2 + 0.02721 \rho \eta^2 - 0.8101 \rho r + 1.3148 \eta^2 - 0.001496 \eta^2 \rho + 0.00353 \eta \rho^2, \\
&\quad -2.916 \eta^2 \rho^2 + 0.89133 \rho \eta^2 \rho + 0.78781 \rho \eta \rho^2 + 0.29969 \rho^2 + 0.03255 \rho \eta^2 \rho + 0.30145 \rho \eta^2 \rho^2.
\end{align*}
\]

(\text{A-1})

\[
\begin{align*}
\frac{f_s}{\mu} &= 0.57 - 0.33608 s - 0.7528r - 1.3403 \eta - 0.1504 \rho + 0.1317 \eta r + 0.1111 \eta^2, \\
&\quad -0.5415 \rho^2 + 0.3359 \eta \rho^2 + 0.8056 \rho \eta - 0.8361 \eta \rho + 0.221 \eta^2 \rho + 0.0661 \eta \rho^2, \\
&\quad -0.02437 \eta^2 - 1.2208 \eta \rho^2 + 1.8419 \eta^2 \rho - 0.1805 \eta^2 \rho^2 - 0.16317 \rho, \\
&\quad +0.07514 \rho^2 - 0.68327 \rho \eta + 0.041867 \eta \rho + 0.00154 \eta \rho^2.
\end{align*}
\]

(\text{A-2})

\[
\begin{align*}
\frac{P}{r^2} &= 1.6835 r - 1.415 \eta + 0.2037 \eta^2 + 0.9017 \eta r + 1.161 \eta^2 - 0.30375 \eta^2 \rho, \\
&\quad -1.4186 \eta^2 \rho + 0.04271 \eta \rho^2 - 0.01784 \rho \rho^2 + 0.43945 \eta \rho^2.
\end{align*}
\]

(\text{A-3})

where \( \sigma = \log (\alpha) \)

Table 2. Mathematical expressions used in the on-line model.

Fig. 8. (a) The effect of roll angular velocity on the non-dimensional parameters, (b) the effect of strip inlet temperatures on the non-dimensional parameters.

Table 1. The reference sets and perturbed sets of process variables.

| R (mm) | \( \omega \) (rad/sec.) | \( T_i \)(°C) |
| --- | --- | --- |
| 250 | 5/5 | 7/7 |
| 500 | 5/5 | 7/7 |
| 750 | 5/5 | 7/7 |

Table 2. The reference sets and perturbed sets of process variables.

| Reference Sets |
| --- |
| Perturbed Sets |
| Perturbed process variables | range of perturbation | \( s \) | \( r \) | \( H_1 \) |
| \( \sigma \) \( \tilde{\epsilon} \) \( \varepsilon \) | plain carbon steel: (C=0.01) \( 0.35 \) | 3 | 0.2 | 5.5-13.9 |
| \( \sigma \) \( \tilde{\epsilon} \) \( \varepsilon \) \( T_i \) | Stainless steel (SUS304): 800 \( \sim 1100 \) °C (see reference 3) | 3-5 | 0.2-0.5 | 2-10 |
| \( \eta \eta \) | HSS, s.g. cast iron, Nickel, A25105: (see reference 3) | 3 | 0.5 | 5.5 |
| \( \rho \rho \) | 250-650 nm | 0.7-3 | 0.2-0.4 | 3.4-118 |
| \( \rho \rho \) | 350-650 mm, 901 °C, 29.2 rad/sec. | 6.5 | 0.2 | 1.4-2.6 |
| \( \rho \rho \) | 400-650 mm, 901 °C, 10.3 rad/sec. | 7.1 | 0.4 | 2.2-4.1 |
| \( \rho \rho \) | 5-10 rad/sec. | 1-5 | 0.1 | 0.5-178 |
| \( \rho \rho \) | 0.01-1.5 W/mm²°C | 3-5 | 0.2 | 0.5-178 |
| \( \rho \rho \) | 750-1100 °C | 1-5 | 0.1 | 0.5-178 |
The following computational procedure may then be taken to calculate roll force and roll power. Suppose the flow stress characteristics of the strip material is given. Then,

1. Read \( R, \omega, H_1, H_2, T_1, \mu \)
2. Calculate \( s, r \)
3. Calculate \( f_s \) from Eq. (A-1) in Table 2
4. Calculate \( \Delta T \), if a proper model is available for its calculation. If not, assume \( \Delta T = 0 \).
5. Calculate \( P' \) from Eq. (1)
6. Calculate \( P \) from Eq. (A-2) in Table 2
7. Calculate \( F \) from Eq. (A-3) in Table 2

The values predicted from the FE process simulation were compared to those predicted from the on-line model. For the values of forward slip, the differences were less than 10 percent for all the sets (reference and perturbed) of process conditions tested, as shown in Fig. 9(a). On the other hand, the values calculated from Orowan’s theory were found to be markedly different from those predicted from the FE process simulation, especially when \( s \) was small, as shown in Fig. 9(b). As shown in Fig. 10, an excellent agreement was noted for the values of roll power and roll force, although \( \Delta T = 0 \) was assumed. Note that the differences were less than 5 percent in most cases. This was in contrast to the values of roll power and roll force calculated from Orowan’s theory, which were substantially smaller than those predicted from the FE process simulation, especially when \( r \) was small, as shown in Fig. 11. The increase in the differences as \( s \) was increased was believed to be arising mainly from the fact that as \( s \) becomes larger, the effective strain rate becomes higher than the strain rate calculated on the basis of homogeneous deformation, and also, the strip temperature becomes smaller than the inlet temperature due to extended roll-strip contact, which led to poorer estimation of the flow stress when Orowan’s theory was used.

6. Concluding Remarks

Investigated in detail was the effect of diverse process variables on some selected non-dimensional parameters characterizing the thermo-mechanical behavior of the strip, via process simulation with an integrated FE process model. Then, it was shown that an on-line prediction model could be developed for roll force and roll power on the
basis of these non-dimensional parameters. Predictions from the present model were in excellent agreement with those from the FE process model for a variety of different process conditions.

It should be noted that a better prediction accuracy could be achieved if a proper model is available for the evaluation of the temperature changes in the bite region. With proper implementation of the effect of strip tension and roll flattening as well as the effect of recrystallization and phase transformation of the strip, along with precise prediction of the strip inlet temperatures, the present model is expected to serve as an effective tool for precision process control in hot strip rolling.

Nomenclature

- \( F \): roll force per unit strip width
- \( H_1 \): strip inlet thickness
- \( H_2 \): strip exit thickness
- \( P \): roll power per unit strip width \((P/2 \text{ for each roll})\)
- \( R \): roll radius
- \( r \): reduction ratio
- \( s \): shape factor, \( s = \frac{2}{2-r} \sqrt{\frac{Rr}{H_1}} \)
- \( T \): temperature
- \( T_1 \): inlet temperature of the strip
- \( T_2 \): exit temperature of the strip
- \( V_1 \): strip inlet speed
- \( V_2 \): strip exit speed
- \( \varepsilon \): effective strain
- \( \dot{\varepsilon} \): effective strain rate
- \( \sigma \): flow stress
- \( \mu \): coefficient of Coulomb friction
- \( \omega \): roll angular velocity
- \( f_s \): forward slip, \( f_s = \frac{V_2 - R\omega}{R\omega} \)
- \( h_{\text{lab}} \): heat transfer coefficient at the roll–strip interface
- \( h_{w1} \): heat transfer coefficient at the water spray zone
- \( T_w \): temperature of the spray water

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