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Application of the Preliminary Displacement Principle to the Temper Rolling Model

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A mathematical model for the analysis of roll gap phenomena in the strip temper rolling process is described. A new approach to solve the roll indentation and diverging problem in modeling of severe temper rolling cases is obtained by adopting the preliminary displacement principle of two contacted rough bodies to describe the friction behavior in the roll gap. The mechanical peculiarities of the temper rolling process, such as a high friction value with high roughness rolls and a non-circular contact arc, low reduction and non-negligible entry and exit elastic zones as well as central preliminary displacement zone etc., are all taken into account. The deformation of work rolls is calculated with the influence function method and an arbitrary contact arc shape is permitted. The strip deformation is modeled by the slab method and the entry and exit elastic deformation zones are included. The preliminary displacement principle is used to determine the boundaries and to calculate the friction of the central preliminary displacement zone. The model is calibrated against the production mill data and installed in the setup computer of a temper rolling mill in POSCO. The validity and precision of the model have been proven through a comparison of the measured roll forces and the predicted ones.

Key Words : Preliminary Displacement Principle, Temper Rolling, and Mathematical Model

1. Introduction

In strip mill operations, the temper rolling (or skin pass rolling) of steel products constitutes parts of the normal manufacturing procedure. With an annealed strip to be subsequently formed, temper rolling provides a slight reduction (0.5~2%) in thickness, and thereby eliminates the yield-point extension in the stress-strain curve of the steel. This, in turn, permits the material to be formed without developing Lueders Lines. Besides, temper rolling is also used to impart the desired surface finish to the product and to improve its flatness.

In order to thoroughly eliminate the yield-point extension, and at the same time to reserve the biggest formability for the subsequent deformation process, the elongation of each strip product must be strictly controlled to a certain value in the temper rolling process. For this purpose, an accurate elongation control system is needed. A mathematical model, which can predict the roll force, torque and forward slip accurately, is also a very important part of this elongation control system.

Empirical models can be used in the real production, but they produce very poor results in some cases, for a lack of physical sense. Thus, the physically based models developed from the mechanical principles are of great importance.

From the viewpoint of mechanics, temper rolling has some peculiarities which need specific care by development of physical model.

1) High friction value.

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2) Low reduction.

3) Relatively large non-slip zone in the central part, especially in dry temper rolling conditions or when high roughness rolls are used.

In modeling the temper rolling process, these peculiarities should be particularly considered.

Untill now, in almost all theoretical temper rolling models, either Coulomb's law (slipping friction) or Tresca's law (sticking friction) has been adopted to describe the friction behavior in the roll gap (Roberts, 1972; Gratocos and Onno, 1994; Carlton et al., 1990). However, neither Coulomb's law nor Tresca's law can describe the friction behavior in a temper rolling process with enough precision. These friction laws overestimate the friction stress in the central part. When the pressure distribution is calculated using these friction laws, an overestimated high "friction hill" is built in the central part of the roll gap. Furthermore, the overestimated "friction hill" causes a roll indentation when calculating the roll deformation. This phenomenon usually makes the calculation process diverge (Grimble, 1996). In order to solve this problem, Domanti et al (1994) and Yuen et al (1996) applied the foil rolling models developed by Fleck et al (1987; 1992) to the temper rolling process. However, unlike that of the foil rolling process, the force of normal temper rolling is usually not large enough to build the central flat region because the soft annealed material is rolled and the reduction is slight. Besides, neglect of the entry and exit elastic zones (Domanti et al., 1994; Fleck et al., 1992) and simplification of the roll deformation mechanism (Yuen et al., 1996; Fleck et al., 1987) as well as difficulties in determination of the boundaries of different zones (Dixon and Yuen, 1995) make it difficult to apply the models on line.

Because the mechanical essence of the Fleck models (Fleck et al., 1997; 1992) is to reduce the friction force and "friction hill" in the central part by assuming the central region being flat and non-slipping, we can expect a similar effect if we adopt a more precise friction law which predicts much lower friction in the central part than Coulomb and Tresca's friction laws.

In modeling the cold rolling process, there are two friction assumptions that predict lower friction in the central part. One is assuming a sticking zone and a restricted deformation zone when the friction stress is larger than the yield stress in shear (Ginzburg, 1985). Another is assuming pure hydrodynamic lubrication in the roll gap (Atkins, 1974). However, neither of these two assumptions is suitable for the temper rolling process, because the relatively low pressure in temper rolling stops the friction stress from exceeding the shear yield stress and the high roughness of roll makes the pure hydrodynamic lubrication impossible.

After surveying the new research achievements in the field of friction study, the authors believe that the preliminary displacement principle (Kragelsky et al., 1982) should be a better description of the friction behavior in the temper rolling process. By using the preliminary displacement principle, the friction and "friction hill" in the central part can be greatly reduced and the roll indentation problem can be solved in normal temper rolling cases. Therefore, in the present paper, the authors apply the preliminary displacement principle to the temper rolling process and develop a new temper rolling model based on the non-circular arc cold rolling model developed by Grimble (1978). The model has been calibrated using the data collected from a production temper rolling mill in POSCO and installed in the setup calculation computer of the same mill. The validation and precision of the model were proven by a comparison of the predicted and measured mill data.

2. Main Equations

The rollgap model is based on two relationships that enable a gauge profile to be calculated from a known pressure profile and conversely a pressure profile to be calculated from a gauge profile. A geometric sketch of the deformation zone is shown in Fig. 1. All equations are expressed under the polar coordinates system.

The elastic deformation of the work roll is related to the roll pressure via the linear integral equation

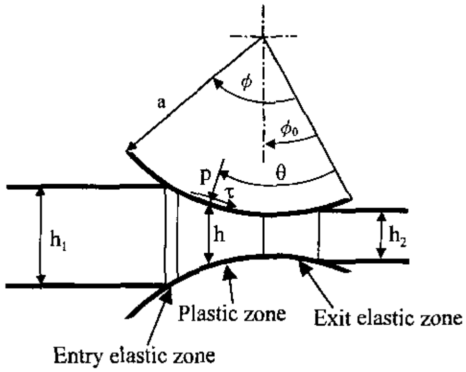


Fig. 1 Sketch of the deformation zone

$$a(\theta)=\int_0^{\phi}U(\theta-t)p(t)dt+R \qquad (1)$$

where : $U(\theta-t)$ — Influence function (Grimble et al., 1978);

$a(\theta)$ — work roll radius at point θ ;

R — undeformed radius of work roll;

$p(t)$ — pressure profile;

ϕ — roll angle represented by the model.

The gauge profile is determined by the deformed roll radius according to the equation

$$h(\theta)=R_s-2a(\theta)\cos(\theta-\phi_0) \qquad (2)$$

where : $h(\theta)$ — gauge profile;

R_s — distance between the centers of the work rolls;

ϕ_0 — angle measured to the line of work roll centers.

The pressure profile is related to the gauge profile via differential equations. In an elastic region, it is (Grimble, 1976):

$$\frac{dp}{d\theta}=-\frac{2a}{h}\left[\frac{\tau v+p(1-2v)\tan\beta}{1-v}+\frac{(2h-h_1)\tan\beta E}{h_1(1-v^2)}\right] \qquad (3)$$

and in a plastic region (Grimble, 1976):

$$\frac{dp}{d\theta}=-\frac{2a}{h}(\tau-ytg\beta)+\frac{dy}{d\theta} \qquad (4)$$

where : v — Poisson's ratio;

E — Young's modulus of elasticity;

h_1 — unstrained gauge in an elastic region;

β — angle between the deformed roll and horizontal axis;

y — yield stress;

τ — friction force between the rolls and the strip;

In the temper rolling process, the strip in the roll gap has both plastic and elastic sections (Lake, 1985; Busch et al., 1987), and the main contact part of the strip with the roll is the elastic section. Thus the friction between the roll and the strip depends mainly on the elastic section, therefore, the preliminary displacement principle between two contacted elastic rough bodies (Kragelsky et al., 1982) can be approximately applied in this case. The friction in the roll gap can be expressed by the following equation (Kragelsky et al., 1982):

$$\tau=\begin{cases}\mu p & \delta>[\delta]\\ \mu p\left\{1-\left[1-\frac{\delta}{[\delta]}\right]^{\frac{2\nu+1}{2}}\right\} & \delta\leq[\delta]\end{cases} \qquad (5)$$

where : μ — friction coefficient;

ν — surface roughness coefficient (Kragelsky et al., 1982);

δ — preliminary displacement;

$[\delta]$ — limiting preliminary displacement.

The preliminary displacement between the surfaces of the roll and the strip can be calculated as follows:

$$\delta=\int_{\phi_n}^{\theta}\left(\frac{h_n}{h(\theta)}-1\right)a(\theta)d\theta \qquad (6)$$

where : h_n — strip gauge at a neutral point;

ϕ_n — nneutral angle;

The limiting preliminary displacement can be determined by the following equation (Kragelsky et al., 1982):

$$[\delta]=\frac{2-\nu}{2(1-\nu)}\mu R_{\max}\varepsilon \qquad (7)$$

where : R_{max} — maximum height of the profile asperities of the work roll surface;

ε — relative approach of the two contact bodies, expressed in a fraction of the highest profile asperity;

Generally, $0\leq\varepsilon\leq 1$. In the temper rolling case, we assume that the relative approach reaches its maximum value, namely $\varepsilon=1$, because the strip is in the mixed elastic plastic status.

Once the pressure and gauge profiles are determined, the roll force, P, torque, T, and forward slip, f, can be calculated as follow:

$$P=\int_0^{\phi} a(\theta)\frac{\cos\beta}{\cos\xi}[p(\theta)+\tau(\theta)\tan\beta]\,d\theta \quad (8)$$

$$T=\int_0^{\phi} a^2(\theta)[\tau(\theta)+p(\theta)\tan\xi]\,d\theta \quad (9)$$

$$f=\frac{h_n}{h_2}-1 \quad (10)$$

where : ξ — angle between the undeformed roll and horizontal axis;

h_2 — strip gauge on the exit side.

3. Calculation Procedure and Results

The iterative procedure is used to solve the equations describing roll deformation and the strip stress distribution. The main flow chart of the calculation procedure is shown in Fig. 2.

Figure 3 is a calculated example of the roll profile, the pressure profile and the friction force distribution calculated by the Grimble model (Grimble et al., 1978) and the present model.

It can be seen that the central part of the roll profile calculated with the Grimble model is greatly flattened. The reason is that the Coulomb's friction law is applied throughout the roll bite and the friction in central part is greatly overestimated by Coulomb's law. When the preliminary displacement principle is applied to describe the friction in the roll bite, the friction hill in the pressure distribution and the central flat region of the roll profile are all smoothed out. The smoothed roll profile makes the calculation process more stable. Compared with the measured pressure profile and friction stress distribution (Lenard, 1992), the pressure profile and the friction stress

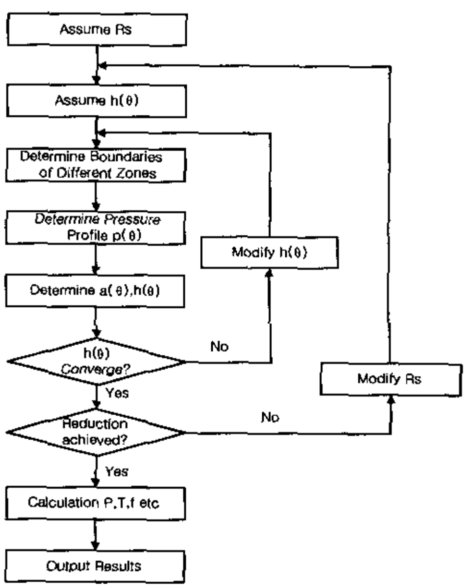
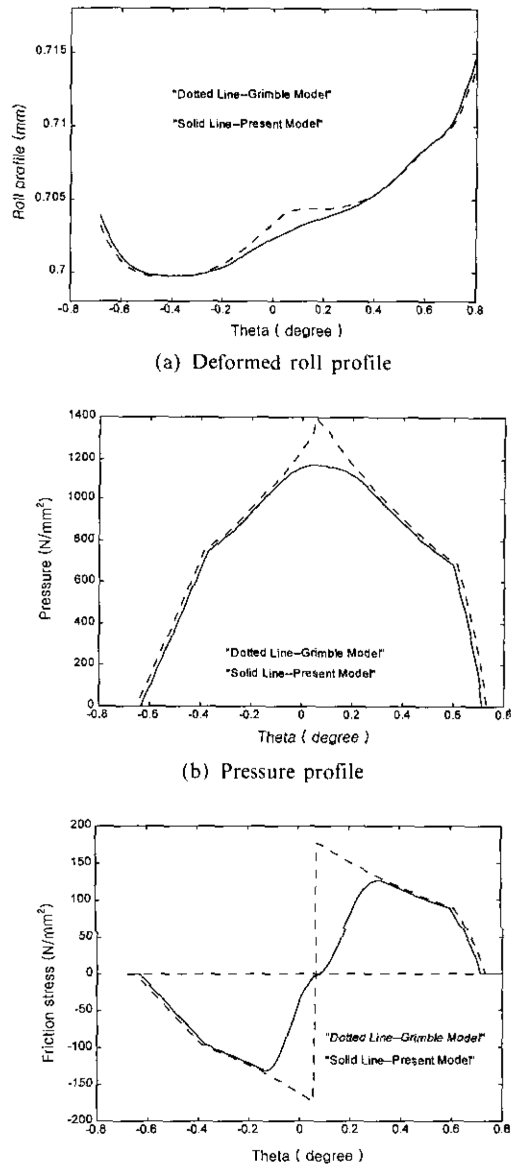


Fig. 2 Main flow chart



(a) Deformed roll profile

(b) Pressure profile

(c) Friction profile

Fig. 3 Deformed roll, pressure and friction profile

profile calculated with present model are more realistic than those calculated with the Grimble model.

4. Model Calibration and Comparison

In order to use the theoretical model as a setup model in the elongation control system of a temper rolling mill in POSCO, the model was calibrated against the production data collected from the mill. The friction coefficient, μ, and the constrained yield stress, K, were taken as the calibration factors. Because the roll force, P, and the forward slip, f, can be measured in the temper rolling mill, and they can also be calculated by the present theoretical model, we use these two measured data to determine the calibration factors K and μ. Equating the measured roll force, P_m, and forward slip, f_m, with their calculation formula, which were derived from the present model, we got two coupled equations. Solving the coupled equations with the iterative method, we obtained the constrained yield stress, K, and the friction coefficient, μ, for each coil. Because the present model can well predict the large forward slip in the temper rolling process, we got reasonable results using the above method. The flow chart of the calibration calculation is shown in Fig. 4.

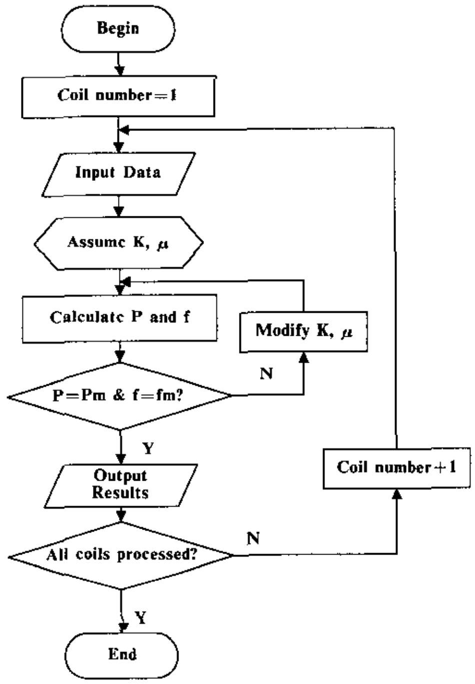


Fig. 4 Calculation of constrained yield stress and friction coefficient

Table 1 The values of the calibration factors for each group

Steel group	Constrained yield stress(N/mm^2)	Friction coefficient
C1CS	282.938	0.13
CCCS	290.369	0.1282
CH35R	213.1372	0.143
CH40R	250.0	0.12
CDCS	179.913	0.1246
CNCS	175.651	0.12681
CECS	166.564	0.1302
CVE1	184.541	0.112115
Mn60	283.2596	0.12676
CH35E	172.931	0.1274
CH40E	172.931	0.1274
CH45E	172.931	0.1274
CH35EB	172.931	0.1274
CT37	263.766	0.1636
CC8H	325.3329	0.12189
CH60C	436.248	0.1143
CX80DP	425.0446	0.18511

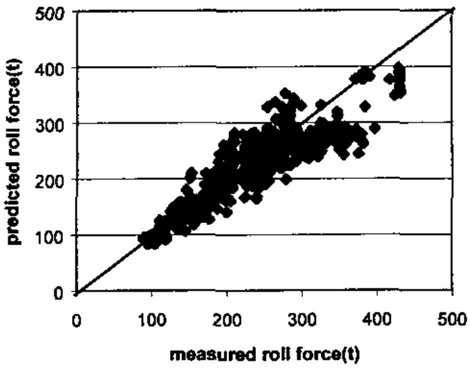


Fig. 5 Measured roll force and that predicted by the present model

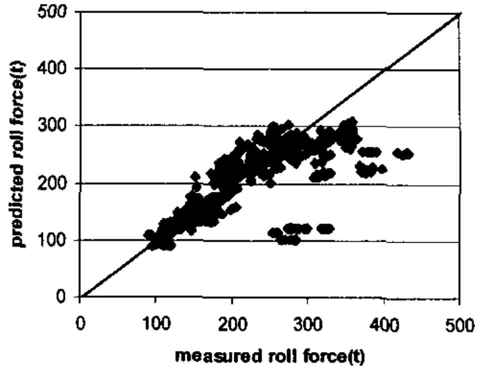


Fig. 6 Measured roll forc and that predicted by the regression model

After the constrained yield stress and friction coefficients were calculated for all coils, we divided the coils into groups according to the steel grades and the constrained yield stress. The average constrained yield stress and average friction coefficient of each group were used as the final values of the calibration factors for this group. Table 1 shows the values of the calibration factors for each group.

After the calibration, the model was installed in the plant together with the data acquisition system to make parallel calculations and comparisons. An evaluation sample that consists of the valid data of 1246 coils was adopted to make the evaluation and the comparison.

Figure 5 shows a comparison of the measured roll forces and the roll forces calculated by the present model. It can be seen that the predicted roll forces match the measured values well and the model has a relatively high prediction accuracy. Statistical analysis shows that the correlation coefficient between the measured roll forces and the roll forces predicted by the present model equals 0.903726

With the same evaluation sample, we also evaluated the regression model that had been used as the setup model in the same temper rolling mill before the present model was developed. Figure 6 shows a comparison of the measured roll force and the roll force calculated by the regression setup model. As we can see, the samples in Fig. 6 are more scattered than the samples in Fig. 5. The correlation coefficient between the measured roll force and the roll force calculated by the regression model is 0.700254. Besides, the average roll force predicted by the regression setup model is lower than that of the measured roll force. This indicates that the regression setup model generally underestimates the roll force. By comparison, we can see that the present theoretical model is much more accurate than the regression setup model. From a comparison with the measured data and comparison with the regression setup model, the validity and precision of the present model were proven.

5. Conclusions

(1) Both Coulomb's friction law and Tresca's friction law overestimated the friction in the central part of the roll gap in the temper rolling process. Because of the overestimation, there may be roll indentation phenomenon when calculating roll deformation through the pressure distribution derived from Coulomb's friction law or Tresca's friction law. This phenomenon often causes the calculation process to diverge.

(2) The preliminary displacement principle can describe the friction behavior in the temper rolling process better than either Coulomb's friction law or Tresca's friction law. By adopting a preliminary displacement principle to the temper rolling model, the roll indentation and divergence problem are solved in normal temper rolling conditions.

(3) Because a more accurate friction law is

adopted and all the peculiarities of the temper rolling process, such as non-circular contact arc, entry and exit elastic zones, are all taken into account in the present model, the model has high prediction accuracy.

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