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A Non-Circular Contact Arc Model for Temper Rolling

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Abstract

A mathematical model for the analysis of roll gap phenomena in strip temper rolling process is described. The mechanical peculiarities of temper rolling process, such as high friction value and non-circular contact arc, low reduction and non-negligible entry and exit elastic zones as well as central restricted deformation (preliminary displacement or sticking) zone etc., are all taken into account. The deformation of work rolls is calculated with the influence function method and arbitrary contact arc shape is permitted. The strip deformation is modeled by slab method and the entry and exit elastic deformation zones are included. The restricted deformation zone near the neutral point is also considered. The concept and the calculation method of limiting preliminary displacement are used to determine the length of the central restricted deformation zone. The comparison of the model results with the measured mill data is also made.

Key words: Temper Rolling, Mathematical Model, and Non-Circular Contact Arc.

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1. Introduction

In strip mill operations, the temper rolling (or skin pass rolling) of steel products constitutes parts of the normal manufacturing procedure. With annealed strip to be subsequently formed, temper rolling provides a slight reduction (0.5~2%) in thickness, and thereby eliminate 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 improve its flatness.

In order to eliminate the yield-point extension thoroughly, and at the same time 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. In addition, a mathematical model, which can predict the roll force, torque and forward slip accurately, is 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 lack of physical sense. Thus, the physical models developed from the mechanical principles are of great importance.

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

1) High friction value. The magnitude of effective friction coefficient in the roll bite is about ten times large than that in conventional cold rolling. Because of the big friction value, the interface between the roll and the strip surfaces appear not to be cylindrical anymore.

2) Low reduction, which means small contact length and non-negligible of entry and exit zones.

3) Because of the high friction value and the low reduction, the restricted deformation (preliminary displacement) zone near neutral point is relatively large and non-negligible, especially in dry temper rolling condition or high roughness rolls are used.

In modeling the temper rolling process, these peculiarities should be particularly considered. Although much research work has been done in the modeling of cold rolling process, the modeling of temper rolling process has not been adequately investigated. Some researchers used the semi-analytical approximation (1). Most researchers modeled the temper rolling process as an extension of the classic cold rolling theory (2~4). No model, which considered all above-mentioned peculiarities of temper rolling process, has so far been reported.

Based on the foil rolling theory proposed by Fleck et al.(5,6), Domanti et al.(7) and Yuen et al.(8) developed the non-circular arc temper rolling models with a central no reduction region. However, numerical simulation showed that the temper rolling force was not large enough to form a central no reduction region in the case of light reduction of annealed soft materials. Especially, it seems to be when the central preliminary displacement zone was taken into account. Besides, neglect of the entry and exit elastic zones (5,7) and simplification of roll deformation mechanism (6,8) in these models will also influence their prediction accuracy. Therefore, the applicable ranges of these models are also very limited.

In this paper, all aforementioned peculiarities of temper rolling process are taken into account. The deformation of work rolls is calculated with the influence function method (9,10). Arbitrary contact arc shape is permitted. The strip deformation is modeled by slab method. The entry and exit elastic deformation zones are included. The restricted deformation zone near the neutral point is also considered. The concept and the calculation method of limiting preliminary displacement (11) are used to determine the length of the central restricted deformation zone. Thus, a complete temper rolling model is developed and the comparison of the model results with the measured mill data is also made.

2. Main equations

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

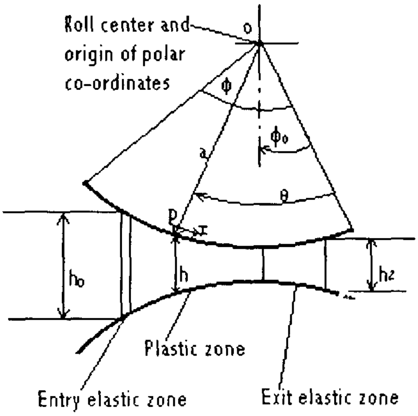


Fig.1 Sketch of deformation zones in temper rolling process.

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

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

where $U(\theta - t)$: Jortner's influence function(9,10)

θ : roll angle measured from initial point

$a(\theta)$: 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 deformed roll radius according to the equation

$$h(\theta) = R_s - 2a(\theta)\cos(\theta - \phi_0) \tag{2}$$

where $h(\theta)$: gauge profile

R_s : distance between 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:

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

and in a plastic region:

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

where υ : Poisson's ratio

E : Young's modulus of elasticity

h_1 : unstrained gauge in an elastic region

β : angle between deformed roll and horizontal

y : yield stress

τ : friction force between rolls and the strip

Two kinds of friction exist in the roll gap: slip friction and preliminary displacement friction. In the slip regions, the friction force is determined with Coulomb law: $\tau = \mu p$ and in the central preliminary displacement region, the friction force is assumed linear distributed:

$$\tau = \frac{\theta - \phi_n}{\theta_s - \phi_n} \tau_s \tag{5}$$

where ϕ_n : neutral angle

θ_s : the boundary of preliminary displacement zone

τ_s : friction force at the boundary of preliminary displacement zone

The boundary of the preliminary displacement zone is determined by the following equation:

$$\left| (\theta_s - \phi_n) R \left(\frac{h_n}{h_s} - 1\right) \right| = [\delta] \tag{6}$$

where h_n : strip gauge at neutral point

h_s : strip gauge at the boundary of the preliminary displacement zone

$[\delta]$: limiting preliminary displacement of the strip-roll contact surfaces

The mechanism of existing the central preliminary displacement zone is that the elastic preliminary displacement on the roll surface matches the plastic displacement of the strip, so that there is no slip between the roll-strip contact surfaces at that region. For this reason, the limiting preliminary displacement in this case can be approximately calculated with the limiting preliminary displacement model of one elastic rough body contact with a smooth body(11):

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

where $R_{\max}$: maximum height of profile asperities of work roll surface

ε : relative approach of two contact bodies, expressed in fraction of the highest profile asperity

Generally, ε lies in the range of $0 \le \varepsilon \le 1$. In temper rolling case, we assume that the relative approach reaches its maximum value, namely $\varepsilon = 1$, because the strip has already had plastic deformation.

Once the pressure and gauge profiles are determined, the roll force P and torque T can be calculated through the integration of the pressure and friction force distribution:

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

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

where ξ : angle between undeformed roll and horizontal

3. Calculation procedure

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

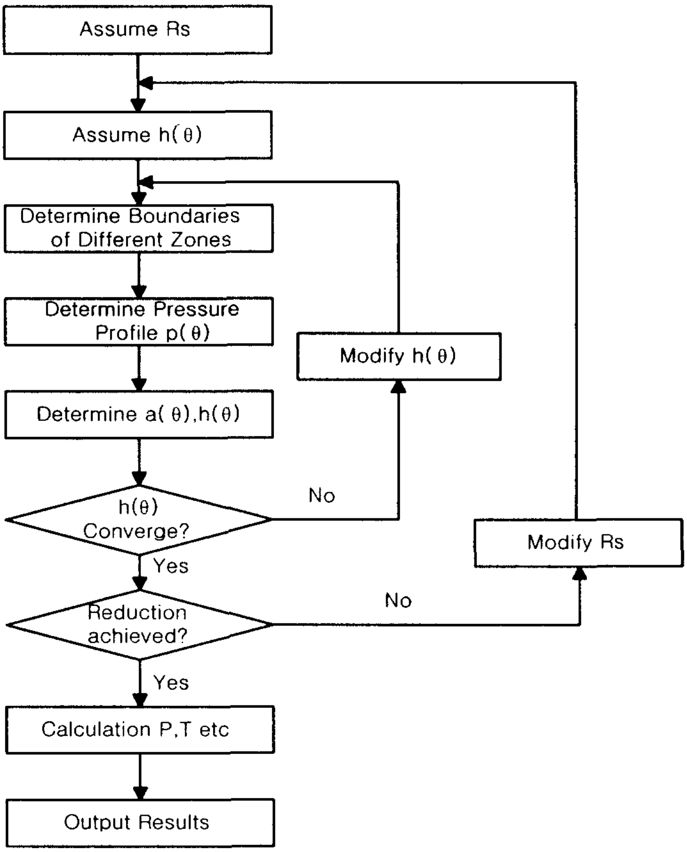


Fig.2 The calculation procedure of the non-circular arc model.

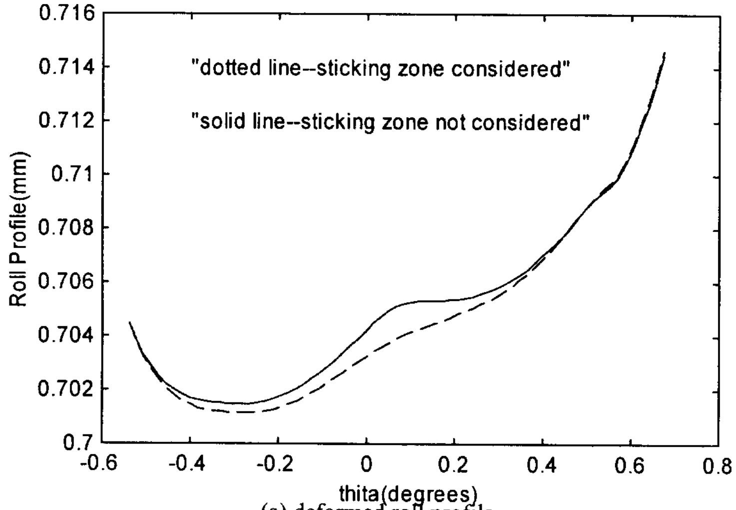
4. Comparison of the results

Fig.3 is a calculated example of the gauge profile, the pressure profile and the friction force distribution with and without consideration of the central preliminary displacement (sticking) zone.

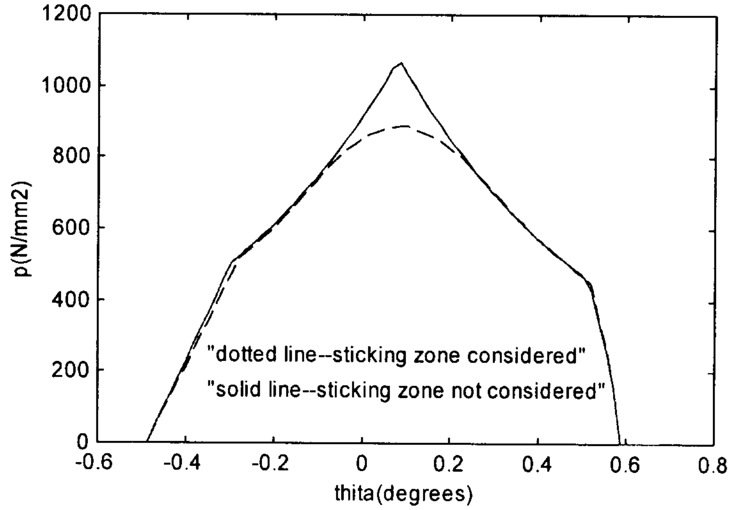
It can be seen that the gauge profile is greatly influenced by considering the central preliminary displacement zone. When the central preliminary displacement zone was not considered, the roll was greatly flattened and formed a flat region near the neutral point. If the load further increase (say, for example, the harder strip is rolled), a roll inflexion will yield, which often causes oscillation to the iterative process and results in divergent(10). When the central preliminary displacement zone was considered, the possibility of roll inflexion is greatly reduced, so that the solution is much more stable and the applicable range of the model is also greatly enlarged. Besides, the pressure profile and the roll force are also quite influenced by considering the central preliminary displacement zone.

The model was calibrated against 100 coils of data from a temper mill in POSCO. The yield stress was estimated from a regression model in which the work hardening effect in temper rolling process was taken into consideration. In addition, the friction coefficients were estimated from the measured roll force using the above model under different products groups. The data of another 210 coils from the same temper mill in POSCO were then used to verify the validity of the model.

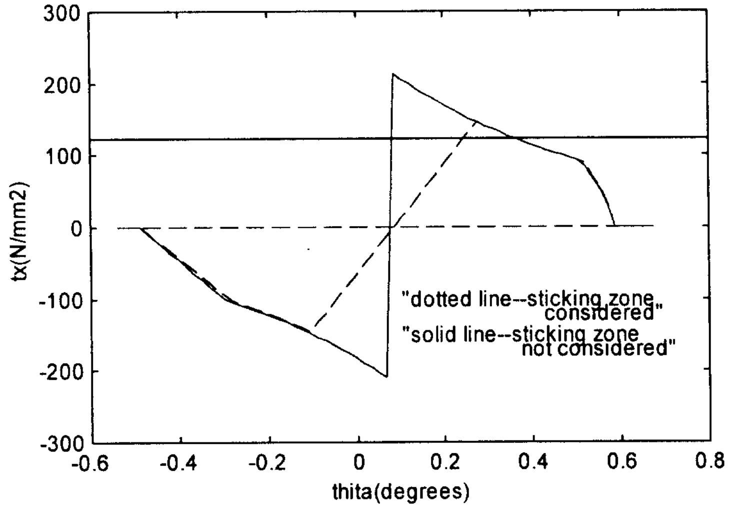
The predicted roll forces and the corresponding measured values are compared in Fig.4. It can be seen that the predicted roll forces match the measured values well, with an overall correlation coefficient of 0.90. However, for very thin strip, as the roll-force increases, the prediction accuracy decreases. When the more precise model for yield stress and friction coefficients are adopted, it is expected that the agreement between the predictions and the measurements will further improve.



(a) deformed roll profile



(b) pressure profile



(c) friction profile

Fig.3 Calculated results for the temper rolling phenomena in roll gap.

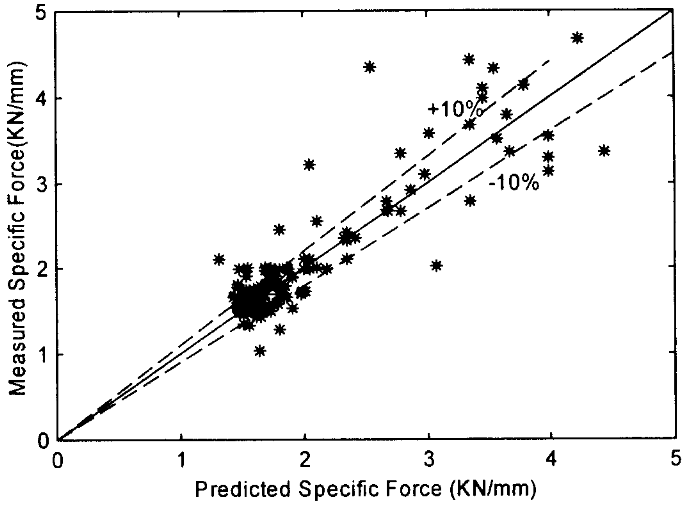


Fig.4 Comparison of predicted and measured roll force.

5. Conclusions

1) Because of the high friction value and the low reduction in temper rolling process, the elastic preliminary displacement on the roll surface matches the plastic displacement of the strip in a relative large region near neutral point. As a result, there is no slip between the roll-strip contact surfaces at that region and a relatively large restricted deformation (preliminary displacement) zone is formed.

2) Preliminary displacement principle of one elastic rough body contact with a smooth body can be adopted to calculate the limiting preliminary displacement and the length of the restricted deformation zone near neutral point in temper rolling process.

3) Because the central preliminary displacement zone is considered in this temper rolling model, the possibility of roll inflexion is greatly reduced. Therefore, the iterative process solving the equations is much more stable and the applicable range of the model is greatly enlarged.

4) Because the peculiarities of temper rolling process, such as non-circular contact arc, entry and exit elastic zones and central preliminary displacement zone, are all considered, present temper rolling model has high prediction accuracy.

5) For very thin strip, as the roll-force increases, the prediction accuracy decreases. This problem needs to be further investigated.

References

1. Roberts,W.L., "An Approximate Theory of Temper Rolling", Iron and Steel Engineer, October 1972, pp.56~68.

2. Carlton,A.J., Edwards,W.J., Thomas,P.J., "Formulae for Cold Rolling Analysis", Proc. AIME Annual Meeting, 1977, Atlanta, Ga., pp.238~248.

3. Carlton,A.J., Edwards,W.J., Thomas,P.J., etc., "Automation of the L.T.V. Steel-Hennepin Two-Stand Temper Mill", 5th International Steel rolling conference, 11~13th September, 1990, London.

4. Busch,M.L., Biausser,H., Biard,G., etc., "Metallurgical and Mechanical Aspects of Temper Rolling Process", Pro. of 4th International Steel Rolling Conference, Vol.2, E48, Deauville, France, June 1987.

5. Fleck,N.A., Johnson,K.L., Mear,M.E. and Zhang,L.C., "Cold Rolling of Foil", Proc. Inst. Mech. Eng., Part B: J. Eng. Man., 206, 1992, pp.119-131.

6. Fleck,N.A., Johnson,K.L., "Towards a New Theory of Cold Rolling Thin Foil", Int. J. Mech. Sci., Vol.29, No.7, 1987, pp.507-524.

7. Domanti,S.A., Edwards,W.J., Thomas,P.J., and Chefneux,I.L., "Application of Foil Rolling Models to Thin Steel Strip and Temper Rolling", Proc. 6th International Rolling Conference, Duesseldorf, Germany, June 20-22nd, 1994, pp.422-429.

8. Yuen,W.Y.D., Nguyen,D.N. and Matthews,D.L., "Mathematical Modeling of the Temper Rolling Processes", 37th MWSP Conf. Proc., ISS,Vol. 33, Ontario, Canada, 1996, pp.165-172.

9. Jortner,D., Osterle,J.F., and Zorowski,C.F., "An Analysis of Cold Strip Rolling", Int. J. Mech. Sci., 1960, Vol.2, pp.179-194.

10. Grimble,M.J., "A Roll-Force Model for Tinplate Rolling", GEC J. of Science & Tech., Vol.43, No.1, 1976, pp.3-12.

11. Kragelsky,I.V., Dobychin,M.N., Kombalov,V.S., "Friction and Wear-Calculation Method", Pergamon Press, Oxford, 1982.