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Analytical Modified Model of Cold Rolling Process and Investigation of the Effect of Work Roll Flattening on the Rolling Force

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Abstract
Cold rolling of steel is one of the most important metal forming processes so an accurate control of its parameters during the process is necessary. In this paper, the friction coefficient has been proposed as a function of cold rolling parameters such as forward slip, forward and backward tensile stresses ,strip thickness, static deformation, resistance of strip before and after rolling ,strip velocity before and after rolling and work roll diameters. A cold rolling model for computation of rolling pressure and force with varying friction coefficient and work roll flattening is proposed. The final results obtained from calculations were very close to the experimental results and there has been a good compliance with this method results and other researches and this is the advantage of this model. Finally the rolling forces in two stands with three passes were measured. So, the results demonstrated that an actual process in the two stand reversing cold mill by increasing the work roll flattening the rolling force increased considerably. Also, by increasing the tensile stresses at the end of the steel strip, the rolling force decreased.

Keywords
Cold rolling, Steel strip, Rolling Force, Roll Flattening

1. Introduction

Cold thin strip can be rolled on a tandem cold mill or a reverse mill where the work rolls are flattened [1]. There are several analytical models presented for this rolling condition. For example for cold rolling of foil [2], rolling of thin foils [3], rolling of thin strip [4] and for rolling elastic deformation of thin strip [5]. In other researches, its shape and flatness have been calculated [6], [7]. The analysis of cold rolling process has attracted the attention of a number of researchers. One of the best methods presented for analyzing the cold rolling processes is the slab method which can be applied for analyzing the rolling force and torque. In this method, a slab of infinitesimal thickness is selected perpendicular to the rolling direction at an arbitrary point in the rolling length. First of all, force balance is made on the element by the slab method. From force balance a differential equation in term of the forming stress is formulated. Then, the constants of integration are derived using appropriate boundary conditions [8].
Friction hills or rolling pressure curves are rolling pressure distribution on every point of the rolling bite. This pressure increases from the entrance plane and has its maximum amplitude at the neutral point. Usually for determining the friction hill coefficient between the roll and strip in the cold rolling conditions, the researchers examine the strip sample. By this method, they calculate the friction coefficient but this coefficient is very different with an actual cold rolling friction

coefficient. Many problems during the cold rolling process are work rolls damage, work rolls flattening, and these problems influence on the friction coefficient. In this paper, the friction coefficient has been proposed as a function of cold rolling parameter such as forward slip, forward and backward tensile stresses, strip thickness, static deformation resistance, and strip velocity before and after rolling, and work roll diameters. Based on this model, we proposed a model for computing the rolling pressure and load during the cold rolling.

2. Equations for Analyzing the Cold Rolling

In this study, a new model for cold rolling of steel strips in the two stand reversing cold mill, was investigated. At the first, a coil is fed into the pay off reel and it was passed among two stands and its end was clamped at the delivery reel. The first pass passes among the pay off reel and the delivery reel. And the second pass will be passed on the opposite direction between the delivery reel and the input reel and the third pass will be done in the opposite direction between the same reels [9-11].

2.1 Forward slip

During an actual cold rolling, the exit speed of strip is greater than the peripheral speed of the work rolls. This difference is the forward slip of rolling.

$$f_s = \frac{v_0 - v_r}{v_r} \tag{1}$$

Where $v_0$the output is seed of the strip and v_r is the peripheral speed of work roll. Bland and Ford showed that the forward slip should be computed as a function of cold rolling parameters and strip geometry [10- 12].

$$f_s = \left(\tan\sqrt{\frac{\zeta}{2}}\,H_n\right)^2 \tag{2}$$

$$\frac{h_0}{R'} = \zeta(h_0\,, R') \tag{3}$$

$$H_n = H_n(\xi, h_i, h_o, \sigma_f, \sigma_b, K_i, K_o, \mu) \tag{4}$$

k_i and k_0 are the resistances to the deformation of strip before and after rolling. The other parameters needed are:

$$H_1 = \left(\frac{2}{\sqrt{\zeta}}\tan^{-1}\frac{\Phi_1}{\sqrt{\zeta}}\right) = \left(\frac{2}{\sqrt{\zeta}}\tan^{-1}\frac{\frac{h_i - h_0}{R'}}{\sqrt{\zeta}}\right) \tag{5}$$

$$H_n = \left(\frac{h_1}{2}\right) - (2\mu^{-1})\ln\left\{\left(\frac{h_i}{h_0}\right)\frac{\left(1-\frac{\sigma_f}{k_0}\right)}{\left(1-\frac{\sigma_b}{k_i}\right)}\right\} \tag{6}$$

And finally, the friction coefficient during the cold rolling is:

$$\mu = \frac{g^2 k}{g^1 f_s} = \frac{\ln\left(\frac{\left(\frac{h_i}{h_n}\left(1-\frac{\sigma_f}{k_n}\right)\right)}{H_1-\left(\left(\frac{4}{\sqrt{\xi}}\right)\tan^{-1}\sqrt{f_s}\right)}\right)}{H_1-\left(\frac{4}{\sqrt{\xi}}\right)\tan^{-1}\sqrt{f_s}} \quad (7)$$

3. Rolling pressure and load

Because of its high accuracy and integrating the rolling load by the part to part method, Bland and ford's method is one of the best procedures that are used for plotting friction hill curves in the rolling bite. In this method, the friction coefficient is assumed to be constant during the rolling bite. [13-15]. In this paper we used the Bland and ford's model to compute the rolling load and rolling pressure and we proposed a new method for determining the rolling load and rolling pressure in an actual cold rolling mill. In this method, the rolling pressure from input plane to the neutral plane is p^- and the rolling pressure changes from the neutral plane to the exit plane is p^+ .according to the equations 3,4 ,the friction coefficient is:

$$\mu = \frac{\ln\left(\frac{\left(\frac{h_i}{h_n}\left(1-\frac{\sigma_f}{k_n}\right)\right)}{H_1-\left(\left(\frac{4}{\sqrt{\xi}}\right)\tan^{-1}\sqrt{f_s}\right)}\right)}{H_1-\left(\frac{4}{\sqrt{\xi}}\right)\tan^{-1}\sqrt{f_s}} \quad (8)$$

And the roll flattened radius is [8-9]:

$$R' = R\left(1+\frac{C}{\Delta h}.\frac{F}{W}\right) \quad (9)$$

This is the Akulund's model and according to his model, the C amount for the steel rolls is about 0.22×10^{-4}.the rolling pressure on the both sides of the neutral plane is:

$$V = \frac{\ln\left(\frac{\left(\frac{h_i}{h_n}\left(1-\frac{\sigma_f}{k_n}\right)\right)}{H_1-\left(\left(\frac{4}{\sqrt{\xi}}\right)\tan^{-1}\sqrt{f_s}\right)}\right)}{\left(\frac{2}{\sqrt{\xi}}\tan^{-1}\frac{\frac{h_i-h_0}{R'}}{\sqrt{\xi}}\right)-\left(\frac{4}{\sqrt{\xi}}\right)\tan^{-1}\sqrt{f_s}} \quad (10)$$

$$p^+ = 2k_f\left(1-\frac{t_f}{2k_f}\right)\frac{h}{h_f}e^{Vh} \quad (11)$$

$$p^- = 2k_0\left(1-\frac{t_b}{2k_0}\right)\frac{h}{h_o}e^{V(H_o-H)} \quad (12)$$

$$H_o = 2\sqrt{\frac{R'}{h_1}}\tan^{-1}\left(\sqrt{\frac{R'}{h_1}}.\alpha\right) \quad (13)$$

In these equations the t_b and t_f are the backward and forward tensile stresses, $2k_f$ and $2k_0$ are the static deformation resistance of the strip after and before rolling and those are determined from the two dimensional tensile test. (h) is the strip thickness at every point t of the rolling bite and h_0 is the initial thickness of the strip and h_f is final thickness of the strip. Based on the equation (11), equations (9), (10) will be changed into equations (7), (8)

$$p^{+} = 2k_f\left(1-\frac{t_f}{2k_1}\right)\frac{h_f+R'\phi^2}{h_f}e^{V\left(2\sqrt{\frac{R'}{h_f}}\tan^{-1}\sqrt{\frac{R'}{h_f}}\phi\right)} \quad (14)$$

$$p^{-} = 2k_0\left(1-\frac{t_b}{2k_0}\right)\frac{h_f+R'\varphi^2}{h_0}e^{V\left(H_0-(2\sqrt{\frac{R'}{h_f}}\tan^{-1}\sqrt{\frac{R'}{h_f}}\varphi)\right)} \quad (15)$$

By equalizing the rolling pressure at the both sides of the rolling bite, the neutral point will be determined.

$p^{+} = p^{-} \rightarrow$

$$2k_f\left(1-\frac{t_f}{2k_1}\right)\frac{h_f+R'\varphi^2}{h_f}e^{V(2\sqrt{\frac{R'}{h_f}}tan^{-1}\sqrt{\frac{R'}{h_f}}\varphi)} \quad (16)$$

$$2k_0\left(1-\frac{t_b}{2k_0}\right)\frac{h_f+R'\varphi^2}{h_0}e^{V\left(H_0-(2\sqrt{\frac{R'}{h_f}}tan^{-1}\sqrt{\frac{R'}{h_f}}\varphi)\right)} \quad (17)$$

By solving the Equation (14), the position of neutral point will be determined according to the Equation (15).

$$\delta = \left(\frac{1}{2\sqrt{\frac{R'}{h_f}}\tan^{-1}\sqrt{\frac{R'}{h_f}}}\right)\left(\frac{1}{2\mu}\ln\frac{2k_0\left(1-\frac{t_b}{2k_0}\right)}{2k_f\left(1-\frac{t_f}{2k_1}\right)}+\frac{\mu H_0}{2}\right) \quad (18)$$

Where, according to the equation (15), we proposed a new relation for finding the neutral point and in this relation, δ is the function of tensile stresses, flattened roll radius, friction and strip thickness at the neutral point

And so on the rolling load is [12, 13]:

$$F = RW\int_0^{\alpha} P\, d\varphi \quad (19)$$

$$F = RW\{\int_0^{\delta} 2k_0\left(1\frac{t_b}{2k_0}\right)\frac{h_f+R'\varphi^2}{h_0}e^{\nu\left(H_0-\left(2\sqrt{\frac{R'}{h_f}}\tan^{-1}\sqrt{\frac{R'}{h_f}}\varphi\right)\right)}d\varphi + \int_{\delta}^{\alpha} 2k_f\left(1-\frac{t_f}{2k_1}\right)\frac{h_f+R'\varphi^2}{h_f}e^{\nu\left(2\sqrt{\frac{R'}{h_f}}\tan^{-1}\sqrt{\frac{R'}{h_f}}\varphi\right)}d\varphi \tag{20}$$

By increasing the number of points, the accuracy of the friction hill plotted will be more. All the presented information is actual and those are similar to an actual cold rolling process in the two stand reversing cold mill.

This information contains product and rolling properties, which they are listed in table (1) and (2).

Table1. Mechanical and physical properties of the St 1008 strip

Strip properties	
□ = *0.29*, □ = *200*□□□, $□_□$ = *280* □□□, $□_□$=658$□_□^{0.24}$ **ρ**=7.782 $\frac{□□□}{□^3}$	material St1008(AISI&SAE STANDARD)
W=1000 mm	Strip width
The roll radius before rolling □ = *240* □□	The rolling stand properties

Table2. The rolling system properties

Pass	stand	($□_0$)initial thickness (mm)	Final thickness ($□_f$) (mm)	Backward tensile stress ($□_□$)		Forward tenslie stress ($□_□$)		Friction coefficient (***μ***)
				Mpa	ton	Mpa	ton	
1	1	2	1.3	10.3	2.1	185.41	24.57	0.05
	2	1.3	0.86	185.41	24.57	108.14	9.48	0.06
2	2	0.86	0.56	108.14	9.48	195.7	11.17	0.03
	1	0.56	0.4	195.7	11.17	164.81	6.72	0.05
3	1	0.4	0.31	164.81	6.72	206.01	6.51	0.04
	2	0.31	0.25	206.01	6.51	65.1	1.71	0.03

4. Results and Discussion

Fig.1 illustrates the rolling process in the two stand reversing cold mill. The forward tensile strip exerting on the strip reduces the rolling pressure from the neutral plane to the exit plane and it moves the neutral point position to the entrance direction. Increasing number of rolling passes increases the work roll flattening and rolling load. Increasing rate of rolling load when the rolls are rigid, is less than when the rolls begin to flat.

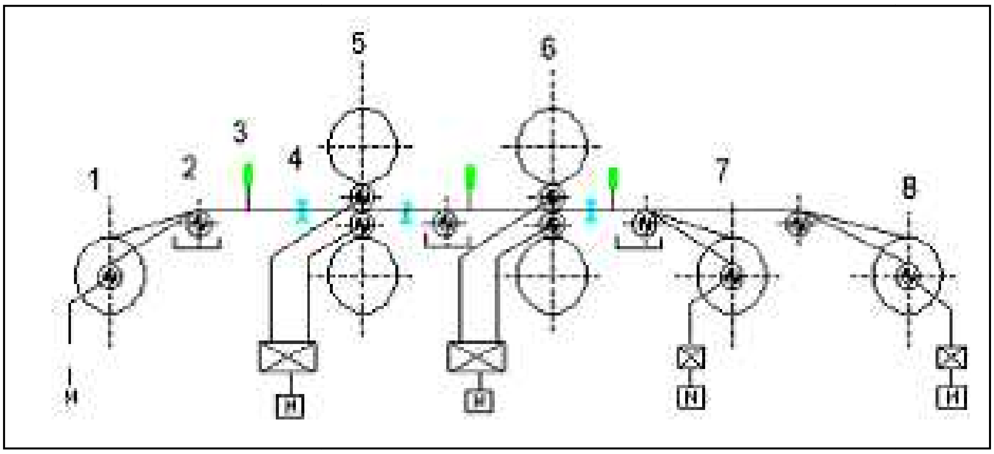


Figure1. A 2-stand tandem cold strip mill. (1) Coiling #2, (2) tension meter, (3) Laser velometer, (4) thickness gauge, (5) stand #2, (6) stand #1, (7) coiling Machine #1 and (8) uncoiling machine

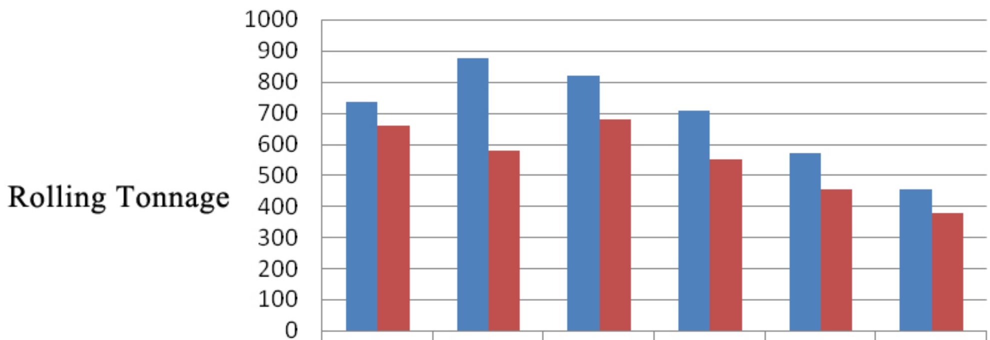
Because of the roll flattening, there is a severely increasing of rolling forces in the final passes. As it is demonstrated in Figs. 2-5, the forward tensile stress exerting at the end of the strip decreases the pressure at the output plane of rolling bite and also it decreases the work hardening of the strip. Backward tensile stress exerting at the end of the strip moves the position of the neutral point toward the exit plane and it also decreases the rolling pressure at the entrance plane of the rolling. This decreasing amount at the exit plane is based on the equation (18) and it is based on the equation (19) at the entrance plane.

Because of increasing the frictional surface, not only this increases the amount of rolls power, but also it increases the backward slip at the entrance plane [13].

$$□^{+}_{□} = 2□_{□}\left(1-\frac{□_{□}}{2□_{□}}\right) \quad (21)$$

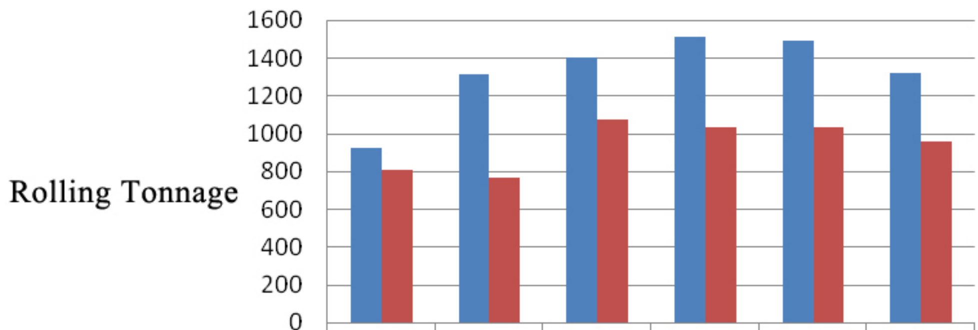
$$P^{-}_{f} = 2k_0\left(1-\frac{t_b}{2k_0}\right) \quad (22)$$

According to Figures 2 and 3, increasing the tensile stresses at the end of the strip decreases the rolling force. The forward tensile stress decreases the rolling pressure at the outside of the rolling bite and vice versa. Also, in this state, the work hardening of the steel strip decreases considerably.



	pass1-stand# 1	pass1-stand# 2	pass2-stand# 2	pass2-stand# 1	pass3-stand# 1	pass3-stand# 2
Without tensile stresses	733.2	877	821.25	707.2	570	455.5
with tensile stresses	658.3	577.1	680.66	552.1	454.3	377.9

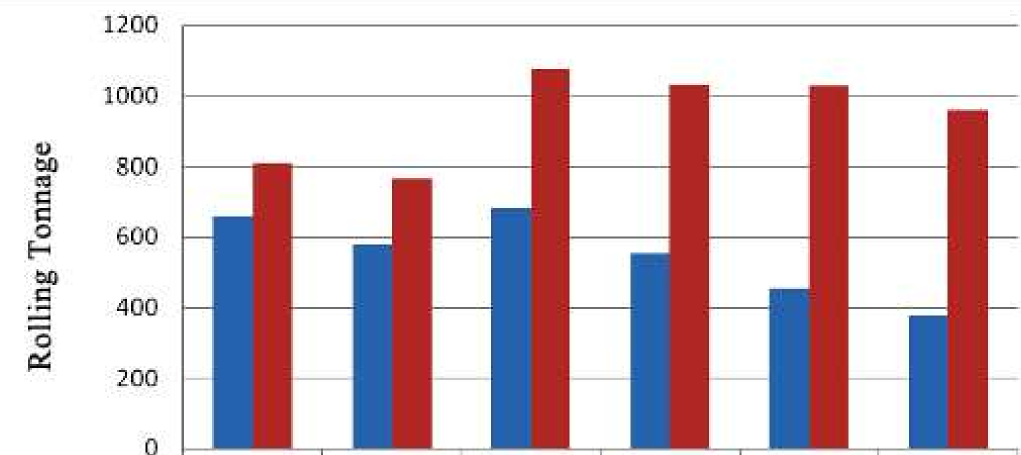
Figure2. Effect of tensile stresses on the rolling force (work rolls are rigid)



	pass1-stand# 1	pass1-stand# 2	pass2-stand# 2	pass2-stand# 1	pass3-stand# 1	pass3-stand# 2
Without tensile stresses	920.34	1315.304	1400	1514	1487.64	1318
with tensile stresses	810.14	764	1076.15	1033.25	1029.3	959.06

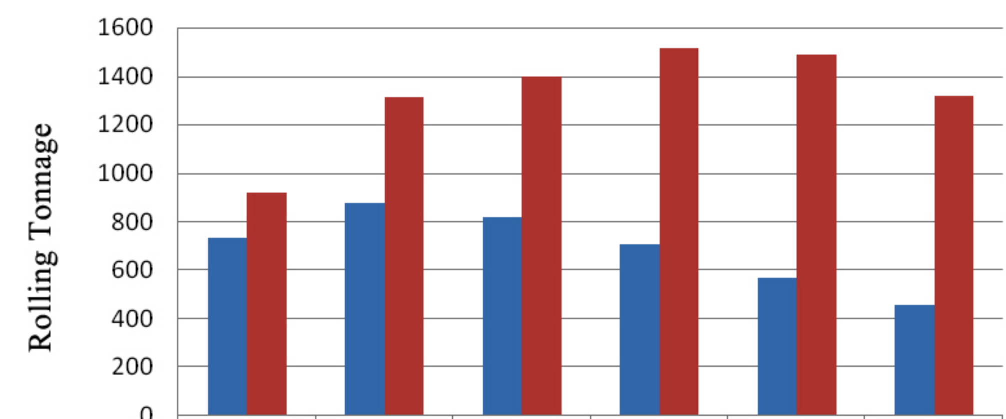
Figure3. Effect of tensile stresses on the rolling force (work rolls are flattened)

Figures 4 and 5 illustrate the effect of work rolls hardening on the rolling force. By increasing the roll flattening amount, the area between the rolls and strips increases which leads to increasing the shear stresses due to frictional forces [16, 17].



	pass1-stand#1	pass1-stand#2	pass2-stand#2	pass2-stand#1	pass3-stand#1	pass3-stand#2
Rigid roller	658.3	577.1	680.66	552.1	454.3	377.9
Flat roller	810.14	764	1076.15	1033.25	1029.3	959.06

Figure4. Effect of work roll flattening on the rolling force (with tensile stresses)



	pass1-stand#1	pass1-stand#2	pass2-stand#2	pass2-stand#1	pass3-stand#1	pass3-stand#2
Rigid roller	733.2	877	821.25	707.2	570	455.5
Flat roller	920.34	1315.304	1400	1514	1487.64	1318

Figure5. Effect of work roll flattening on the rolling force (without tensile stresses)

5. Conclusion

1. The most work hardening and residual stresses are in the first pass.
2. Tensile stresses applied to the ends of strip decrease the rolling pressure.
3. Backward and forward tensile stress exerting at the end side of strip decrease the rolling pressure at the rolling bite.
4. Work rolls flattening severely increase the rolling force due to increasing the shear stresses along the rolling bite.

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