A study on the Relative Slip Chracteristics in Continuous Rolling Process of Rail with Forward Pull

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Abstract. In continuous rail rolling by universal mill, the forward-slip coefficient is one of the most important parameters to control the rollling process. Firstly the forward-slip coefficient of the web in a single stand without tension has been proposed by considering the influencing factors as many as possible. Then the tension between two adjacent stand has been represented and the forward-slip coefficient with forward pull has been derived. Moreover, the experiments of two-stand continuous rolling of rail by universal mill has been accompolished to get the forward slip coefficient of web of rail with forward pull. The theoretical results is in agreement with the experimental data basically and approaches that well.

Notation

α_h , α_{vb} , α_{vt} Bite angle of the horizontal roll,the vertical roll for rolling the base of rail and the top of rail respectively

H_{w0} , H_{w1} The height of the web of rail at the entrance sectionThe height of the web of rail at the exit section respectively

H_{b0} , H_{b1} The height of the web of rail at the entrance section The height of the base of rail at the exit section

W_{b0} , W_{b1} The width of the base of rail at the entrance sectionThe width of the base of rail at the exit section

W_{t0} , W_{t1} The width of the head of rail at the entrance section The width of the head of rail at the exit section

R_h The radius of horizontal roll R_{vb} The radius of vertical roll for rolling the base of rail

$\overline{G_{vt}}$, G_{vt} The equivalent gap of the vertical roll rolling the top of railThe gap of the vertical roll rolling the top of rail

$\overline{D_{vt}}$ The equivalent diameter of vertical roll for rolling the base of rail

$\overline{p_h}$ Mean unit pressure acting on the web from the horizontal roll

$\overline{p_{vt}}$, $\overline{p_{vb}}$ Mean unit pressure acting on the top of rail and the base of rail from the vertical roll

p_{ht} , p_{hb} Mean unit pressure acting on the top of rail from the flank of horizontal roll   acting on the rail bas

μ_{hw} Friction coefficient between the web and horizontal roll

μ_{ht} , μ_{hb} Friction coefficient between the top of rail ,the rail base and the flank of horizontal roll

μ_{vt} , μ_{vb} Friction coefficient between the top of rail, the base of rail and vertictal roll

X_w , X_v the horizontal resultant force acting on the web of rail and the base of rail

X_{ft} , X_{fb} the horizontal resultant force acting on the top of rail and the base of rail from the flank of horizontal roll

ρ the proportion factor about horizontal resultant force X_{ft} and X_{fb}

L_t the length of deformation zone in rolling the base and top of rail

1. Introduction

Since 1970s, the universal rolling methods has been applied in H-beam rolling widely and the theoretical research about that has been carried out, and the numerical simulation by FEM has been used in universal rolling prosess[1-4].Then the theory of universal rolling methods has been developed and improved. Although the universal rolling methods has been also applied in rail rolling for 30 years, there are few theoretical research about the rail rolling by universal mills.W.Zhang and Q.Zhou[5,6] studied the deformation mechanism and force-energy parameters by energy principle and variational methods during H-Beam universal rolling in single stand. X.Jin [7]built the theoretical model of velocity field, plastic flow and relative slip in the Continuous Rolling Process of H-beam, and accomplished the H-beam universal rolling experiments. In previous work of author, Y.Dong and J.Song proposed the theoretical model for calculating the rolling force[8], plastic flow law[9-11], cross-section temperature[12] and forward slip coefficient[13,14] during the rail universal rolling in single stand by upper-bound principle and energy methods. At present, the application of universal mill becomes more and more prevalent in producing the high-precision rail, and it has been taking the place of conventional producing methods gradually. Continuous rolling method is a high efficiency rolling method and it has been applying in strip rolling and rod rolling generally.However, the continuous rolling method has not been applied in rail universal rolling widely since the relative slip characteristics of rail universal rolling is hard to be predicted precisely and then the rolling speed of two adjacent stand is hard to set. So the .For the certain similarity of Heavy Rail rolling and H-beam rolling, the result of theoretical research about H-beam rolling can be applied as an available reference in Heavy Rail rolling.
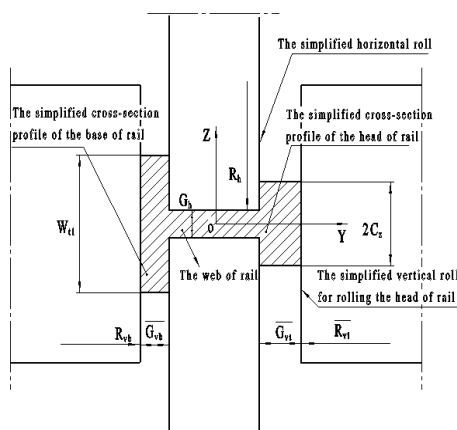

Figure 1. Simplified model of universal rolling of Heavy Rail
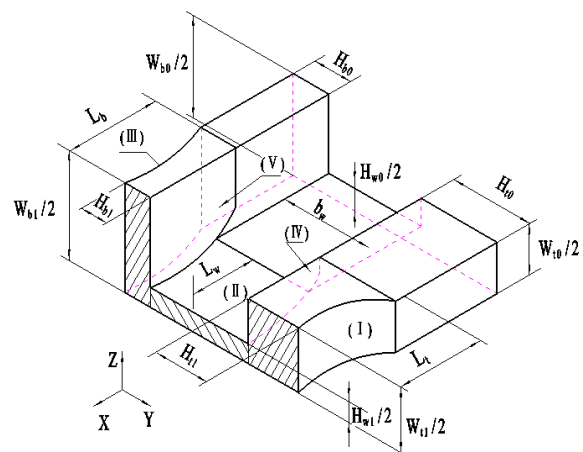
Figure 2. Schematic plan of deformation zone

   The universal mill consists of four rolls, two horizontal drive rolls and two vertical driven rolls (**Fig.1**). The size of two horizontal rolls is identical, but the vertical roll of rolling the top of rail is different from that of rolling the base of the rail. The vertical roll of rolling the top of rail is flat, but the box pass has been grooved on the vertical roll of rolling the top of the rail. In Heavy Rail rolling,

there are 5 deformation zone existing in the deformed workpiece (**Fig.2**): (Ⅰ)the deformation zone between the vertical roll and the top of rail; (Ⅱ) the deformation zone between the horizontal roll and the web of rail ;(Ⅲ) the deformation zone between the vertical roll and the base of rail; (Ⅳ) the deformation zone between the side of horizontal roll and the top of rail; (Ⅴ) the deformation zone between the side of horizontal roll and the top of rail. The top view of rail universal rolling was shown as **Fig.3**, the two rolls were vertical roll for rollling the base of rail and head of roll.

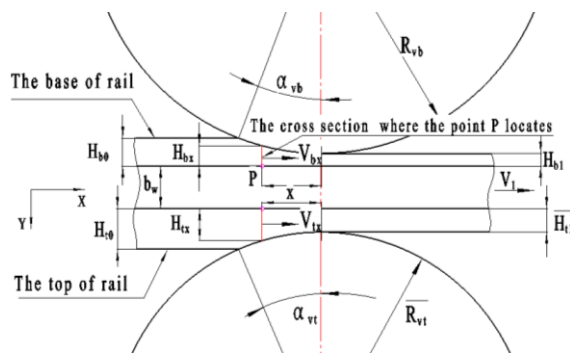## 2. The Simplified Model Of Vertical Roll Of Rolling The Top Of Rail

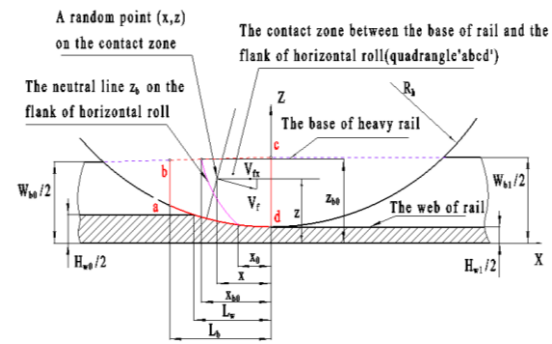**Figure 3.** The top view of rail universal rolling

Figure 4. The neutral line on the side of horizontal roll
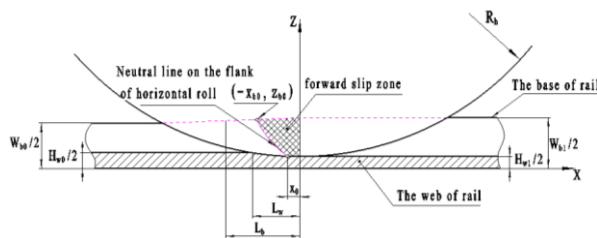

Figure 5. forward slip zone on the side of horizontal roll
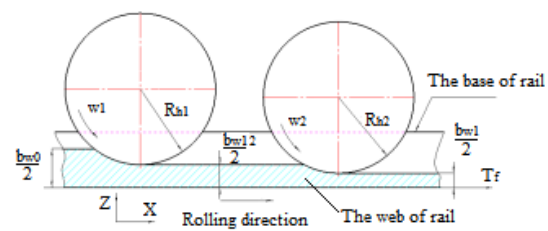

Figure 6. Continuous rolling of rail in two stand

In earlier work by Yonggang Dong and Wenzhi Zhang[10-12], the influence of base of rail and top of rail on the forward coefficient of the web of rail was studied and the neutral line on the deformation (Ⅳ) and deformation (Ⅳ) were determined to distinguish the forward slip zone and backward slip zone on this two deformation zones. The deformation zones was shown in **Fig.2** and the derivation of neutral line on the side of horizontal roll were shown as **Fig.4** and **Fig.5**.

3. Forward-Slip Coefficient Of The Web In Single Stand Without Forward Pull
Forward-slip coefficient is one of the most important parameters in the automatic tension control of the continuous rail rolling process by universal mill. For the great differences in the conditions of roll and workpiece, there are two different metal flow existing in the deformation zone. When the forward-slip coefficient of the web δ_w is greater than unity, forward-slip and backward-slip occur synchronously. However, when δ_w is less than unity, the complete backward-slip occurs.

The forward-slip coefficient of the web is always less than unity on the condition that a thicker web, wider base or top of rail, large reduction ratio and an backward pull are present. On the contrary, the coefficient is greater than unity in all other cases. However, whatever are the rolling conditions, the forward coefficient between the vertical roll and base is always greater than unity.

In reference[13,14], if the forward slip coefficient between the horizontal roll and the web of rail in a single stand without tension is not less than1, it can be obtained by Eq.1 and Eq.2

If $x_{b0} < L_b$

$$\delta_{w0} = 1 + \frac{1}{b}\left[\frac{\overline{p_h}b_w L_w \mu_{hw}}{\overline{p_{hb}}\mu_{hb}}\left(1-\frac{\alpha_h}{2\mu_{hw}}\right) + (1+\rho)L_f\left(W_{b0}-H_{w1}\right)\left(1-\frac{2}{L_f}\sqrt{\frac{H_{b1}\cdot 2R_{vb}\left(W_{b0}-H_{w1}\right)}{2R_h-W_{b0}+H_{w1}}}\right) + \frac{X_v}{\overline{p_{hb}}\mu_{hb}}\right]$$

where b is expressed as

$$b = (1+\rho)\left(50\sqrt{\frac{\left(0.01R_h+W_{b0}-H_{w1}\right)^3 H_{b1}\cdot 2R_{vb}}{2R_h-W_{b0}+H_{w1}}} - 0.28R_h\sqrt{R_h H_{w1}} - 50\left(W_{b0}-H_{W1}\right)\sqrt{\frac{H_{b1}\cdot 2R_{vb}\left(W_{b0}-H_{w1}\right)}{2R_h-W_{b0}+H_{w1}}}\right) + \frac{14\overline{p_h}b_w\mu_{hw}}{\overline{p_{hb}}\mu_{hb}}\sqrt{H_{w1}R_h}$$

If $x_{b0} \geq L_b$

$$\delta_{w0} = 1 + \frac{\dfrac{\overline{p_h}b_w L_w \mu_{hw}}{\overline{p_{hb}}\mu_{hb}}\left(1-\dfrac{\alpha_h}{2\mu_{hw}}\right) + (1+\rho)L_f\left(W_{b0}-H_{w1}\right)\left(1-\dfrac{2}{L_f}\sqrt{\dfrac{H_{b1}\cdot 2R_{vb}\left(W_{b0}-H_{w1}\right)}{2R_h-W_{b0}+H_{w1}}}\right) + \dfrac{X_v}{\overline{p_{ht}}\mu_{ht}}}{2(1+\rho)\left(R_h L_f - 0.14R_h\sqrt{H_{w1}R_h}\right) + \dfrac{14\overline{p_h}b_w\mu_{hw}}{\overline{p_{hb}}\mu_{hb}}\sqrt{H_{w1}R_h}}$$

Forward Slip Of The Web Between Two Adjacent Stand With Tension

The tension force during H-beam continuous rolling had been proposed by X.Jin[6]. By the similar method, the tensile force of continuous rail rolling between two adjacent stand can be represented (**Fig.6**)

$$\sigma_{12} = \frac{\delta_{w0.2}R_{h2}\left(\dfrac{W_2}{W_1}\cdot\dfrac{S_2}{S_1}\right) - \delta_{w0.1}R_{h1}}{G_2 R_{h2}\left(\dfrac{W_2}{W_1}\right) + G_1 R_{h1}}$$

Where $\delta_{w0.1}, \delta_{w0.2}$ is the forward-slip coefficient of the web in stand 1 and stand 2 without tension, respectively, and can be obtained by Eq.(1), Eq.(2) or Eq.(3) and Eq.(4) according to the position of neutral line. $W_2, W_1, S_2, S_1, R_{h1}, R_{h2}, G_2, G_1$ are the angle velocity of horizontal roll in stand 1 and stand 2 , the cross-section area of deformed workpiece in stand 1 and stand 2, the radius of horizontal roll in stand 1 and stand 2, the influence coefficient of vertical roll in stand 1 and stand 2, respectively. G_1, G_2 can be shown as

$$G_1 = \frac{S_1}{\left[2(1+\rho)\overline{p_{ht}}L_{b1}f_{ht}\right]}$$

$$G_2 = \frac{S_2}{\left[2(1+\rho)\overline{p_{ht}}L_{b2}f_{ht}\right]}$$

Then, the forward-slip coefficient of the web with tension can be shown as

$$\delta_{w1} = \delta_{w0.1} + \frac{\sigma_{12}\cdot S_1}{2(1+\rho)\overline{p_{ht}}L_{b1}f_{ht}}$$

$$\delta_{w2} = \delta_{w0.2} + \frac{T_f - \sigma_{12}\cdot S_2}{2(1+\rho)\overline{p_{ht}}L_{b1}f_{ht}}$$

4. Results and discussions

According to Eq.(1), Eq.(3), the forward slip coefficient during single stand universal rolling without tension can be obtained, then the forward slip coefficient during two adjacent stand universal rolling with tension can be calculated by Eq.(7) and Eq.(8).The size of rolling pieces was shown as Fig.7, and the corresponding parameters was shown as Table1.
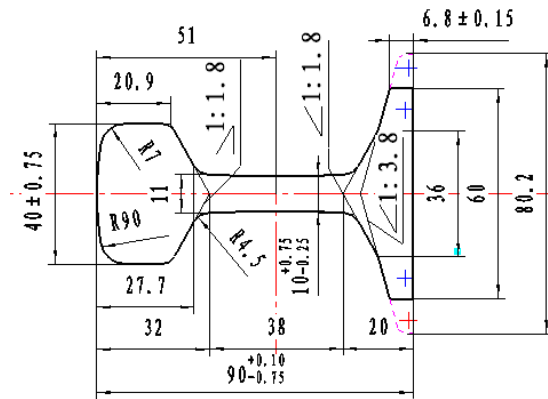

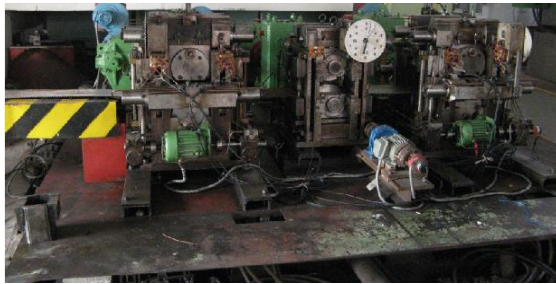**Figure 7.**Cross-section size of initial rolling pieces

Figure 8. The three-stand universal experimental mills

Figure 9. Figure 10. Measurment of hump marks on the web of rail

Table 1. Calculation Result From The Theoretical Model

Parameters Stand No.	Parameter of simplifying the vertical roll(mm)				Neutral angle(rad)			Neutralline (mm)		Forward slip coefficient
	R_{vb}	R_h	$\overline{D_{vt}}$	$\overline{H_{vt}}$	γ_h	γ_{vb}	γ_{vt}	x_{t0}	x_{b0}	δ_{w0}
Stand1	210	140	200	40	0.0328	0.0482	0.0522	10.2	8.8	0.972
Stand2	190	120	180	36	0.0333	0.0490	0.0531	9.3	7.4	0.983

Table 2. The Rolling Schedule For 18kg/M Light Rail Universal Rolling Experiments

Workpiece No.	Reduction (mm)			Main motor speed (rpm)	Horizontal roll rotating velocity (rad/s)	Workpiece's temperature(℃)	
	The web of rail	The head of rail	The base of rail			Heating temperature	Initial rolling temperature
Stand1	1.0	2.5	1.5	1200	3.9873	1050	1000
Stand2	0.8	2.0	1.2	1000	3.3228	1040	995

Table 3. Calculation Result Of Tension In Continuous Rolling

Parameter	G_1 (mm³/ N)	G_2 (mm³/ N)	L_{f1} (mm)	L_{f2} (mm)	S_1 (mm²)	S_2 (mm²)	f_{ht}	$\overline{p_{ht}}$ (N/mm²)	σ_{12} (N/mm²)
Value	0.79	1.15	8.9	8.1	2100	1920	0.15	208	0.04

For verifying results from the theoretical model, a piece of 18kg/m light rail(Fig.8)was heated and rolled in the three stand universal mill of Yanshan University, the rolling equipments were shown as Fig.8(a) and Fig.8(b). The rolling schedule was shown as Table.2

The forward pull can be imposed on the workpiece and adjusted by the tension control system of three-stand universal rolling mills. Two little dents with constant distance was chisled on the surface of horizontal rolls, and the forward slip coefficient can be obtained by mearsuring the distance between two hump marks on the web of rail after rolled(Fig.9) and and calculated the diatance ratio between the two dents on the roll and two hump marks on the workpiece.

The experimental data and theoretical results were shown in **Fig.11.**

In continuous rolling process, the tension between two adjacent stand has been calculated and results is shown in **Table 3.** And then the forward-slip coefficient of the web with backward pull and forward pull is expressed in **Fig.11(a) and Fig.11(b).** As can be seen in **Fig.11,** there exists **a little** discrepancy between the theoretical results and experimental data, and either theoretical results or experimental data, the forward-slip coefficient of the web becomes greater with the increment of forward pull.

(a)First Stand   (b)Second Stand
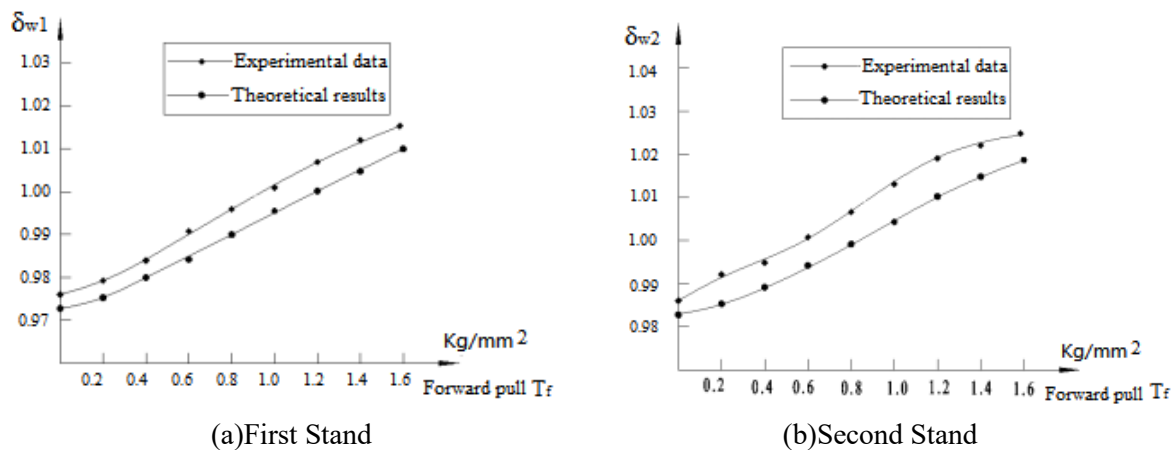
Figure 10. The forward-slip coefficient of the web with forward pull:

5. Conclusion

In this paper, the method of force equilibrium has been employed to derive a series of equations for forward-slip coefficient, which is applicable to different rolling conditions, for example the size of workpiece and pass schedule.

(1) The forward pull influences the forward-slip coefficient of the web greatly. The forward-slip coefficient of the web becomes greater with the increment of forward pull;

(2) With the incresement of forward full, the relative slip status of the web of rail changes from the backward slip to forwad slip against the horizontal roll;

(3) The theoretical results is in agreement with the experimental data basically and approaches that well. So, thistheoretical model can be applied in universal continuous rolling of rail.

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