Experimental study on deformation region types and percentages of each region in asymmetrical rolling of strip

Xiangkun Sun, Xianghua Liu, Junlong Qi and Ji Wang

State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang, 110819, China

Abstract. A simple method for dividing the deformation type and a practical model for calculating the percentages of each region in various deformation types are proposed. The percentage of cross-shear zone gradually increases to 100% and the percentages of forward-slip and backward-slip zone gradually decrease to 0 as rolling pass increases with huge roll force and tensions and better lubricating conditions. The method and the model can provide a good reference for better operations during asymmetrical rolling, which is good for rolling industry.

1. Introduction

In asymmetrical rolling process, the radius, peripheral velocity and the surface roughness of the upper roll may be different from those of the lower roll, can gain such benefits as lower rolling pressure distribution, roll force and roll torque. Unlike symmetrical rolling, the peripheral velocity of the upper roll is different from that of the lower roll in asymmetrical rolling and the two neutral points at each side of the strip do not coincide. Thus, in addition to the backward-slip zone and forward-slip zone, a third zone known as cross-shear zone appears, where the upper and lower surface frictions act in opposite directions. The percentages of each region have great impact on rolling pressure distribution, roll force and roll torque.

A series of analytical and experimental works on asymmetrical rolling have been performed by many researchers. Huang and coworkers [1, 2] developed an model for asymmetrical cold rolling on slab method to investigate the behaviors of sheet during asymmetrical rolling and they sued theoretical analysis such as stream function method [3] and finite element method [4] to analyze the process further. Salimi and Sassani [5] built a theoretical model to predict the outgoing curvature of the sheet by studying the variations of the normal and shear stress strains within the roll gap. They assumed linear shear stress distribution along the thickness of the slab. Wang and Liu [6] proposed a model based on slab method to analyze the effects of mechanical parameters including roll speed, roll diameter and friction coefficient on rolling pressure, roll force and roll torque in asymmetrical rolling. Zhang and Zhao [7] developed a model considering the shear stress along the vertical sides of each slab. Aboutorabi and Assempour [8] analyzed the sheet output curvature in asymmetrical rolling by slab method considering the rolls horizontal displacement. Tzou and Hwang [9, 10] developed four analytical models based on the slab method for minimum thickness in asymmetrical PV rolling. Qwamizadeh and coworkers [11] developed a model based on the slab method considering the developed curvature in asymmetrical sheet rolling to calculate the strip curvature. Furthermore, they [12, 13] analyzed the asymmetrical rolling of bonded two-layer sheets where the ingoing sheet is...
forced to horizontally enter the roll gap. Wang and Zhang [14] proposed an approach for asymmetrical rolling of two unbonded clad sheet layers and they used the vertical stresses in clad sheet asymmetrical rolling and the calculation results were in better agreement with the results of the experiments. However, the specific methods of distinguishing each deformation region type and calculation methods of the percentages of each region in asymmetrical rolling are rarely studied and so do the effects of rolling parameters on the percentages of each region.

In this paper, a method for dividing the deformation type and a model for calculating the percentages of each region in various deformation types are proposed. Several experiments were done to study the changes of percentages of each region with various roll forces, lubrication conditions and back and front tensions.

2. Mathematical models
To simplify the formulation involved in developing the analysis in asymmetrical rolling, the following assumptions are employed:

1) The rolls and work pieces are rigid-plastic bodies and the diameter of the upper roll is the same as the lower roll;
2) The plastic deformation is plane strain;
3) The stresses are uniformly distributed within the elements. The vertical stress and horizontal stress are regarded as principal stresses;
4) The contact lengths on the upper and lower rolls are equal and the contact arc is simplified as string.

2.1. Deformation region types

Figure 1 is a schematic illustration of asymmetrical strip rolling, where \( V_f \geq V_s \). The plastic deformation region is divided into three regions according to the positions of the upper and the lower neutral point. These regions are denoted as zone I for the backward-slip zone, zone II for the cross-shear zone, and zone III for the forward-slip zone. Not all the three regions exist in every asymmetrical rolling process. The deformation region type of asymmetrical rolling varies due to the peripheral speeds of the upper and lower roll \( v_f \) and \( v_s \), the linear speeds of strip at the inlet and outlet \( v_H \) and \( v_h \), the neutral angles of the upper and lower roll \( \alpha_f \) and \( \alpha_s \) and the contact angle of the roll gap \( \alpha_t \). When \( v_s \cos \alpha_s > v_H, v_f \cos \alpha_f < v_h \), the deformation region type is B+C+F, which means the plastic deformation zone includes backward-slip zone, cross-shear zone and forward-slip zone. If \( v_H < v_s \cos \alpha_s < v_h, v_f \geq v_h \), the deformation region type is B+C. Similarly, the deformation
region type is C+F when \( v_H < v_f \cos \alpha_f < v_h, v_s \cos \alpha_s \leq v_H \) and \( v_s \geq v_h \) for deformation region type of OB, \( v_f \cos \alpha_f \leq v_H \) for deformation region type of OF and \( v_f \geq v_h, v_s \cos \alpha_s \leq v_H \) for deformation region type of OC. Deformation region type of OC refers to that only cross-shear zone exists in the deformation zone and it is usually called as asymmetrical PV rolling. The six types of deformation region in asymmetrical strip rolling are shown in Figure 2.

![Six types of deformation region in asymmetrical strip rolling.](image)

**Figure 2.** Six types of deformation region in asymmetrical strip rolling.

### 2.2. Percentages of each region

The percentages of each region are defined as the ratios of horizontal projection lengths of each region to the contact length. Figure 3 is a schematic geometry of plastic deformation region in asymmetrical rolling of strip. The percentages of the backward-slip zone, cross-shear zone and forward-slip zone are denoted as \( Q_b = \frac{l_b}{l} \), \( Q_c = \frac{l_c}{l} \) and \( Q_f = \frac{l_f}{l} \), respectively. Where \( l_b, l_c \) and \( l_f \) are lengths of the backward-slip zone, the cross-shear zone and the forward-slip zone, respectively, and \( l \) is the length of contact.

![Schematic geometry of plastic deformation region.](image)

**Figure 3.** Schematic geometry of plastic deformation region.

When the deformation region type is B+C+F, referring to geometries in Figure 1 and Figure 3, we have

\[
Q_b = \frac{l_b}{l} = \frac{h - h_b}{h - h} \times 100\% \tag{1}
\]

\[
Q_c = \frac{l_c}{l} = \frac{h_b - h}{h - h} \times 100\% \tag{2}
\]

\[
Q_f = \frac{l_f}{l} = \frac{h_f - h}{h - h} \times 100\% \tag{3}
\]
Where \( h_b \) and \( h_f \) are thicknesses at the lower and upper neutral point, respectively. Referring to the law of volume constancy per second, we have

\[
Hv_H = h_b v_s \cos \alpha_s = h_f v_f \cos \alpha_f = hv_H
\]

(4)

In asymmetrical rolling of strip, the contact length is much smaller than the diameter of the work roll, thus

\[
\cos \alpha_s \approx 1, \cos \alpha_f \approx 1
\]

(5)

Substituting Eqns. (4) and (5) into Eqns. (1), (2) and (3), we have

\[
O_b = \frac{v_H(v_s - v_H)}{v_s(v_H - v_f)} \times 100\%
\]

(6)

\[
O_c = \frac{v_H(v_f - v_f)}{v_f(v_H - v_f)} \times 100\%
\]

(7)

\[
O_f = \frac{v_f(v_f - v_f)}{v_f(v_H - v_f)} \times 100\%
\]

(8)

Similarly, when the deformation region type is B+C, we have

\[
O_b = \frac{v_H(v_s - v_H)}{v_s(v_H - v_f)} \times 100\%
\]

(9)

\[
O_c = \frac{v_H(v_f - v_f)}{v_f(v_H - v_f)} \times 100\%
\]

(10)

\[
O_f = 0
\]

(11)

When the deformation region type is C+F, we have

\[
O_b = 0
\]

(12)

\[
O_c = \frac{v_f(v_f - v_f)}{v_f(v_H - v_f)} \times 100\%
\]

(13)

\[
O_f = \frac{v_f(v_H - v_f)}{v_f(v_H - v_f)} \times 100\%
\]

(14)

When the deformation region type is OB, we get \( O_b = 100\%, O_c = O_f = 0 \), and type of OC for \( O_c = 100\%, O_b = O_f = 0 \) and type of OF for \( O_f = 100\%, O_b = O_c = 0 \).

3. Experiments and discussions
In order to study the percentages of each region in asymmetrical rolling of strip, several experiments were done on the asymmetrical mill as shown in Figure 4, which, the roll force and tensions can be real-time controlled, the diameter of the upper and lower roll are 50.0mm and the speed ratios \( \delta \) are set by two pair of open gear sets, \( \delta = 1.083 \) and \( \delta = 1.174 \). T2 grade copper strip was used, with a thickness of 0.11mm and a width of 40mm.

![Figure 4. Experimental mill and open gear sets.](image)

Figure 5 illustrates the variation of percentages of each region with rolling passes under two speed ratios, \( \delta = 1.083 \) and \( \delta = 1.174 \). The deformation type is B+C+F when the speed ratio is 1.083, and the percentage of cross-shear zone gradually increases to 100%, while the percentages of forward-slip zone and backward-slip zone gradually decrease to 0 with the increasing of rolling passes. When the
speed ratio is 1.083, the deformation type is B+C, the forward-slip zone disappears and percentage of cross-shear zone gradually increases to 50%, while the percentage of backward-slip zone gradually decreases to 50%.

Figure 5. Variation of percentages of each region with rolling passes under two speed ratios, $i = 1.083$ and $i = 1.174$.

Figure 6 shows the variation of percentages of each region with rolling passes under two roll forces $P = 2.5\text{kN}$ and $P = 3.75\text{kN}$. Evidently, when the roll force increases from 2.5kN to 3.75kN, the forward-slip zone appears and the deformation type turns into B+C+F. As rolling pass increases, the percentage of cross-shear zone gradually increases to 100% and the percentages of forward-slip zone and backward-slip zone gradually decrease to 0.

Figure 6. Variation of percentages of each region with rolling passes under two roll forces, $P = 2.5\text{kN}$ and $P = 3.75\text{kN}$.

Figure 7 shows the variation of percentages of each region with rolling passes under different tensions and lubrications. Referring to Figure 6, it can be easily seen that, the forward-slip zone appears when the back and front tensions increase from 15MPa to 30MPa and friction condition changes from dry friction to lubricating oil friction. Similar to increasing of roll force, the percentage of cross-shear zone gradually increases to 100% and the percentages of forward-slip zone and backward-slip zone gradually decrease to 0 as rolling pass increases.
The rolling parameters, such as speed ratio, roll force, lubrication condition and back and front tension have a great impact on the deformation region types and percentages of each region. The foreword-slip zone may disappear with increasing speed ratio and as rolling pass increases the percentage of cross-shear zone gradually increases to 100% and the percentages of forward-slip and backward-slip zone gradually decrease to 0 under the conditions that easily to reduce the thickness, such as huge roll force, back and front tensions and better lubricating condition.

4. Conclusions
1) A simple method for dividing the deformation type and a practical model for calculating the percentages of each region in various deformation types are proposed. The method and the model can provide a good reference for better operations during asymmetrical rolling, which is good for rolling industry;

2) The deformation type and percentages of each region are related to roll force, back and front tension, speed ratio and lubrication. With increasing of roll force and tensions and better lubricating condition, the percentage of cross-shear zone increases while the percentages of forward-slip zone and backward-slip zone decrease. As rolling pass increases, the percentage of cross-shear zone gradually increases to 100% and the percentages of forward-slip zone and backward-slip zone gradually decrease to 0.

Reference
[1] Hwang Y M, Tzou G Y 1996 Stress analysis of asymmetrical cold rolling of clad sheet using the slab method Journal of materials engineering performance 5 621
[2] Hwang Y M, Tzou G Y 1993 An analytical approach to asymmetrical cold strip rolling using the slab method Journal of Materials Engineering and Performance 2 597
[3] Hwang Y M, Chen T H 1996 Analysis of asymmetrical sheet rolling by stream function method Jsme International Journal Series a-Mechanics and Material Engineering 39 598
[4] Hwang Y M, Chen D C, Tzou G Y 1999 Study on asymmetrical sheet rolling by the finite element method Chinese Journal of Mechanics-Series A 15 149
[5] Salimi M, Sassani F 2002 Modified slab analysis of asymmetrical plate rolling International Journal of Mechanical Sciences 44 1999
[6] Wang J, Liu XH, Guo WP 2018 Analysis of mechanical parameters for asymmetrical strip rolling by slab method The International Journal of Advanced Manufacturing Technology 98
2297

[7] Zhang SH, Zhao DW, Gao CR, Wang GD 2012 Analysis of asymmetrical sheet rolling by slab method International Journal of Mechanical Sciences 65 168

[8] Aboutorabi A, Assempour A, Afrasiab H 2016 Analytical approach for calculating the sheet output curvature in asymmetrical rolling: In the case of roll axis displacement as a new asymmetry factor International Journal of Mechanical Sciences 105 11

[9] Tzou G Y, Huang M N 2001 Study on minimum thickness for asymmetrical hot-and-cold PV rolling of sheet considering constant shear friction Journal of Materials Processing Technology 119 229

[10] Tzou G Y, Huang M N 2000 Study on the minimum thickness for the asymmetrical PV cold rolling of sheet Journal of Materials Processing Technology 105 344

[11] Qwamizadeh M, Kadkhodaei M, Salimi M 2012 Asymmetrical sheet rolling analysis and evaluation of developed curvature International Journal of Advanced Manufacturing Technology 61 227

[12] Qwamizadeh M, Kadkhodaei M, Salimi M 2014 Asymmetrical rolling analysis of bonded two-layer sheets and evaluation of outgoing curvature International Journal of Advanced Manufacturing Technology 73 521

[13] Qwamizadeh M, Kadkhodaei M, Salimi M 2013 Slab Analysis of Asymmetrical Rolling of Bonded Two-layer Sheets Isij International 53 265

[14] Wang H, Zhang D, Zhao D-w 2015 Analysis of Asymmetrical Rolling of Unbonded Clad Sheet by Slab Method Considering Vertical Shear Stress ISIJ International 55 1058