Mechanics of cold rolling of thin strip

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Abstract

Cold rolled thin strip has a wide application in electronic and instrument industries, and its production has always been of major interest to the manufacturers and researchers in the area of metal plasticity. Thin strip rolling involves significant metal plasticity to produce a desired product. Iwamoto (2004), Stoughton & Yoon (2004) and Hub et al. (2004) were interested in dealing with the plastic deformation and plastic yielding of steel, and its micromechanics. With the need for higher quality and productivity in cold strip mill, mathematical models of cold rolling of a strip with a desired shape and dimension, both for mill setup and for on-line control, have become a key issue in the steel rolling process. One major part of these models concerns the strip and roll deformation, plastically deformed strip shape and profile. The development of the roll deformation model can be divided into three groups, which includes simple beam model, slit beam model and finite element analysis model (Ginzburg, 1989). Stone & Gray (1965) modelled the roll deformation as the deflection of a simple beam on an elastic foundation. Shohet & Townsend (1968) proposed a slit beam deflection model, and then Edwards & Spooner (1973), Wang (1986) improved this theory and introduced a matrix method to solve the beam deflection considering strip plastic deformation. It has now been widely used in analysis of the roll deformation and strip shape and profile. Timoshenko & Goodier (1970), Jiang et al. (2003a, b, c), Koman (1998) and Lin & Lee (1997) used finite element model and numerical methods to analyse the strip rolling and to improve the simulation accuracy of the strip shape and profile. In order to improve the quality of the produced products, Kim & Oh (2003) used finite element method to analyse grain-by-grain deformation by crystal plasticity with couple stress, Simth et al. (2003) conducted a study of the effect of the transverse normal stress on sheet metal formability and Ho et al. (2004) developed integrated numerical techniques to predict springback in creep forming thick aluminum sheet components. Buchheit et al. (2005) performed simulations of realistic looking 3-0 polycrystalline microstructures generated. The simulation on precipitate induced hardening in crystal plasticity was conducted (Han et al., 2004). Martin & Smith (2005) investigated the influence of the compressive through-thickness normal stress on sheet metal formability and tried to explore the ways to improve the sheet metal formability. However, the finite element analysis is rather complicated and may have a convergence problem, which is difficult to be used for on-line control of the thin strip rolling. An influence function method analysis considering the strip plastic deformation and roll deformation can be directly used in the control of strip rolling, especially in the control of the shape and profile of strip.

Keywords
rolling, thin, strip, cold, mechanics

Disciplines
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20

Introduction

Austria

University of Wuppertal, Mechanical Engineering

School of Mechanical Engineering and Mechatronics

Z. Yan
2. Roll deformation of 4-high rolling mill

The image contains a diagram of a 4-high rolling mill, showing the process of rolling a strip. The diagram includes various labels and measurements, indicating the forces and deformations at different parts of the mill. The text accompanying the diagram explains the mechanics of the rolling process, focusing on the deformation of the strip and the forces involved. It discusses the impact of different factors on the roll deformation and how these forces affect the final product. The diagram is a useful tool for understanding the complexities of the rolling mill operation and the optimization of the rolling process to achieve desired outcomes.
produced by the force $\tau$ is as follows:

When a force $\tau$ acts on the plane at position $O$, the vertical displacement at point $P$ on the plane is $\frac{\tau}{E} \cdot \frac{y}{h}$, where $E$ is the Young's modulus of elasticity, $y$ is the distance from the plane $x = \frac{x}{h}$, and $h$ is the distance between the supports.

The formula for the deflection of the beam at position $x$ is given by:

$$d(x) = \frac{1}{2} \frac{E}{I} (x_I)^2$$

where $I$ is the moment of inertia of the beam's cross-section, $E$ is Young's modulus, and $x_I$ is the distance from the beam's neutral axis.

For a beam with constant cross-section, the deflection at any point $x$ can be calculated using the following formula:

$$d(x) = \frac{1}{2} \frac{E}{I} (x_I)^2 = \frac{1}{2} \frac{E}{I} (x)^2$$

where $I$ is the moment of inertia of the beam cross-section.

The deflection of the beam at position $x$ can be expressed as:

$$d(x) = \frac{1}{2} \frac{E}{I} (x)^2 = \frac{1}{2} \frac{E}{I} (x)^2$$

This equation shows that the deflection of the beam increases with the square of the distance $x$ from the neutral axis.

For a beam with variable cross-section, the deflection at position $x$ can be calculated using the following formula:

$$d(x) = \frac{1}{2} \frac{E}{I} (x_I)^2 = \frac{1}{2} \frac{E}{I} (x)^2$$

where $I(x)$ is the moment of inertia of the beam cross-section at position $x$.

The deflection of the beam at position $x$ can be expressed as:

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$$d(x) = \frac{1}{2} \frac{E}{I} (x_I)^2 = \frac{1}{2} \frac{E}{I} (x)^2$$

where $I(x)$ is the moment of inertia of the beam cross-section at position $x$.

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$$d(x) = \frac{1}{2} \frac{E}{I} (x_I)^2 = \frac{1}{2} \frac{E}{I} (x)^2$$

This equation shows that the deflection of the beam increases with the square of the distance $x$ from the neutral axis.
be expressed as

\begin{equation}
\psi = \frac{\partial f}{\partial t} + \mathbf{u} \cdot \nabla f
\end{equation}

where \( \mathbf{u} \) is the velocity field.

Note: The text appears to be cut off or incomplete in the provided image.
2.5 Placing between the upper and down work rolls

\[ \frac{\left( \frac{z}{x+y} + \frac{x}{y+z} \right) \frac{z}{y+z} \frac{z}{x+y} }{q(z-1)} = (z)q \]

where \( q \) is the distribution of contact pressure along the contact with the upper and down work rolls, which is given by

\[ q = \frac{q}{z} \frac{z}{y+z} \frac{z}{x+y} \frac{\left( \frac{z}{x+y} + \frac{x}{y+z} \right)}{z} = (z)q \]

directly by

\[ (z) = (z)q 

where \( (z)q = \sum_{i=1}^{m} \phi_i \left( \frac{z}{x+y} + \frac{x}{y+z} \right) \frac{z}{y+z} \frac{z}{x+y} \]

is the distribution of contact pressure along the contact with the upper and down work rolls.
2.8 Solution of Equations

\[
\frac{\gamma}{2} = \sqrt{\left(\frac{1}{\gamma} \right)^2 - \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2}
\]

The equations used to calculate the roll and strip deformation and the strip shape as shown in Fig. 6.

2.7 Statically equilibrium of work roll

2.6 Measurement - It can be expressed as Eq. (2):

\[
\frac{\gamma}{2} = \sqrt{\left(\frac{1}{\gamma} \right)^2 - \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2}
\]

The equilibrium of the work roll is obtained by summing vertically the load between the upper and lower roller of the work roll and the lower roller and the upper roller of the backup roll. The equilibrium of the work roll and strip, which is written as Eq. (2),

\[
\frac{\gamma}{2} = \sqrt{\left(\frac{1}{\gamma} \right)^2 - \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2}
\]

The equilibrium of the work roll and strip, which is written as Eq. (2),

\[
\frac{\gamma}{2} = \sqrt{\left(\frac{1}{\gamma} \right)^2 - \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2}
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\frac{\gamma}{2} = \sqrt{\left(\frac{1}{\gamma} \right)^2 - \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2}
\]

The equilibrium of the work roll and strip, which is written as Eq. (2),

\[
\frac{\gamma}{2} = \sqrt{\left(\frac{1}{\gamma} \right)^2 - \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2}
\]

The equilibrium of the work roll and strip, which is written as Eq. (2),

\[
\frac{\gamma}{2} = \sqrt{\left(\frac{1}{\gamma} \right)^2 - \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2 + \left(\frac{1}{\gamma} \right)^2}
\]
An effect of edge contact on specific forces and strip profile

Table 1: Comparison of specific forces and strip down with or without edge contact

<table>
<thead>
<tr>
<th>Width (cm)</th>
<th>Spec. Force (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>620</td>
</tr>
<tr>
<td>30</td>
<td>596</td>
</tr>
<tr>
<td>45</td>
<td>569</td>
</tr>
</tbody>
</table>

Where $H$ is the Groove depth and

$$
rac{h}{l} \cdot \frac{h}{H} = \gamma
$$

and in $m = 0.32\gamma$, $h$ is the effective material reduction which can be described as

$$
\frac{h}{l} \cdot \frac{h}{H} = \gamma
$$

where $h$ is a constant in the equation $h = k \cdot V / \psi$, and in the equation $m = 100$ and $m = 0.32\gamma$, $h$ is a constant in the equation $h = k \cdot V / \psi$.

Equation 2

$$
\gamma = \frac{h}{l} \cdot \frac{h}{H}
$$

Where $x$, $y$, and $z$ are the strain rates and

$$
(C = 10000 \cdot \psi) \cdot \frac{h}{H} = \gamma
$$

Equation 3

$$(H \cdot l)^{0.5} + 1.999 \cdot l = \gamma$$

Where $H$ and $l$ are the entry and exit thicknesses of strip, respectively. $C$ is the yield stress.

Equation 4

$$(H \cdot l)^{0.5} + 1.999 \cdot l = \gamma$$

Where $H$ and $l$ are the entry and exit thicknesses of strip, respectively.
The Effect of the width of the strip on the distribution of exit thicknesses

Table 2: Comparison of specific forces and strip profiles for different exit thicknesses

<table>
<thead>
<tr>
<th>Exit Thickness (mm)</th>
<th>Specific Force (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>12.0</td>
</tr>
<tr>
<td>0.1</td>
<td>11.0</td>
</tr>
<tr>
<td>0.2</td>
<td>10.0</td>
</tr>
<tr>
<td>0.3</td>
<td>9.0</td>
</tr>
<tr>
<td>0.4</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Figure 11: Effect of the width of the strip on the reduction and exit thickness distribution

A. Effect of the width of the strip on the reduction and exit thickness distribution

The reduction and exit thickness distribution of the strip is obtained by integrating the specific force and the exit thickness distribution of the strip on the roll bite. The effect of the width of the strip is observed by comparing the exit thickness distribution of the strip at different widths of the strip. The width of the strip has a significant effect on the reduction and exit thickness distribution of the strip. The wider the strip, the higher the reduction and exit thickness distribution.

Figure 12: Effect of the specific force on the roll bite and exit thickness distribution

The specific force has a significant effect on the reduction and exit thickness distribution of the strip. The higher the specific force, the higher the reduction and exit thickness distribution of the strip. The specific force is obtained by integrating the specific force and the exit thickness distribution of the strip on the roll bite. The effect of the specific force on the roll bite and exit thickness distribution is observed by comparing the exit thickness distribution of the strip at different specific forces.

Figure 13: Effect of the temperature on the roll bite and exit thickness distribution

The temperature has a significant effect on the reduction and exit thickness distribution of the strip. The higher the temperature, the higher the reduction and exit thickness distribution of the strip. The temperature is obtained by integrating the specific force and the exit thickness distribution of the strip on the roll bite. The effect of the temperature on the roll bite and exit thickness distribution is observed by comparing the exit thickness distribution of the strip at different temperatures.
Table 4: Comparison of specific forces and strip crown with different friction coefficients

<table>
<thead>
<tr>
<th>Force (kN/m)</th>
<th>Specific forces (kN/m)</th>
<th>Strip width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.05</td>
<td>0.00</td>
</tr>
<tr>
<td>0.02</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>0.03</td>
<td>0.15</td>
<td>0.10</td>
</tr>
<tr>
<td>0.04</td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>0.05</td>
<td>0.25</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Fig. 14: Effect of friction coefficient on edge thickness distribution and specific forces

Table 5: Comparison of specific forces and strip crown with different strip widths

<table>
<thead>
<tr>
<th>Width of strip (m)</th>
<th>Force (kN/m)</th>
<th>Specific forces (kN/m)</th>
<th>Strip width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.05</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>0.02</td>
<td>0.10</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>0.03</td>
<td>0.15</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>0.04</td>
<td>0.20</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>0.25</td>
<td>0.20</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 15: Effect of the strip width on the roll deflection and flattening (a) specific forces (b) edge contact force
**Figure 17. Effect of transverse friction on specific force**

- **Calculated**
- **Measured**

**Figure 18. Distribution of friction coefficient along the strip width**

- **Calculated**
- **Measured**

---

In the cold rolling process, the friction coefficient is crucial in determining the rolling force and the energy consumption. The friction coefficient at the entry and exit of the rolls is calculated using a specific formula. The calculated forces are compared with the measured forces to assess the accuracy of the model.

The effect of the transverse friction on the final strip profile and specific force is significant. The calculated values are shown in Figure 17, indicating how the friction coefficient affects the rolling forces.

---

**Figure 19. Exit thickness vs. roll width**

- **Calculated**
- **Measured**

The exit thickness from the rolling process is compared with the calculated values to verify the model's accuracy. The thickness variation with roll width is shown in Figure 19, illustrating the consistency between the calculation and measurement.

In order to verify the simulation results, the cold rolling of thin strips was conducted in the laboratory. The comparison of the experimental data with the calculated values confirmed the validity of the model.
The rolling force, which is caused by the contact force and the height of the work roll, affects the strip shape. Improvement of this force can improve the strip profile. The stress exerted on the strip is significant and can affect the width and profile of the strip. The work roll force and the work roll speed have a significant influence on the strip width. The work roll force is applied with an increase of the rolling force. The change in the work roll force is applied with an increase of the rolling force. The change in the work roll force is applied with an increase of the rolling force. The change in the work roll force is applied with an increase of the rolling force.

Influence Function Method

The system is to determine the strip shapes and the direction of the work roll. The work roll force and the work roll speed have a significant influence on the strip width. The work roll force is applied with an increase of the rolling force. The change in the work roll force is applied with an increase of the rolling force. The change in the work roll force is applied with an increase of the rolling force. The change in the work roll force is applied with an increase of the rolling force.

Conclusions

Rolling Process

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5. Conclusions

The rolling process is the work roll force that causes force on the strip. The work roll force has a significant influence on the strip width. The work roll force is applied with an increase of the rolling force. The change in the work roll force is applied with an increase of the rolling force. The change in the work roll force is applied with an increase of the rolling force. The change in the work roll force is applied with an increase of the rolling force.

Fig. 3. Effects of the rolling speeds and strip widths on rolling force

<table>
<thead>
<tr>
<th>Strip Width (mm)</th>
<th>Rolling Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.15</td>
</tr>
<tr>
<td>110</td>
<td>0.15</td>
</tr>
<tr>
<td>120</td>
<td>0.15</td>
</tr>
<tr>
<td>130</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Numerical analysis - Theory and Application
Mechanics of Cold Rolling of Thin Strip

8. References

The work was supported by Australian Research Council (ARC) Discovery-Project grant.

7. Acknowledgments

Thank you, professor...

Appendix A: Calibration of the work roll and backup roll...

Appendix B: Photographs of the work roll and backup roll...

Appendix C: Photographs of the work roll and backup roll...

Appendix D: Photographs of the work roll and backup roll...
Introduction

 emulation model, the transceiver architecture and the performance evaluation of the system. The simulation results show that the proposed system can achieve good performance in terms of bit error rate (BER) and signal-to-noise ratio (SNR), which is comparable to the ideal system. The proposed system is able to provide high-speed data transmission in a noisy environment, making it suitable for a wide range of applications.