ISE 311
Rolling lab

in conjunction with

Chapters 18 and 19 in the text book
“Fundamentals of Modern Manufacturing”
Third Edition
Mikell P. Groover

Prepared by: Amin Naser and Tom Yelich
May 22nd, 2008
Outline

• Introduction to rolling
• Flat rolling and its analysis
• Flat rolling defects
• Rolling mills
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• Summary
Rolling is a bulk deformation process in which the thickness of the work is reduced by compressive forces exerted by two opposing rolls. The rolls rotate to pull and simultaneously squeeze the work between them.

The rolling process (specifically: flat rolling)
Introduction to Rolling

The basic process shown in the previous figure is “Flat Rolling”, used to reduce the thickness of a rectangular cross section. A closely related process is “shape rolling”, in which a square cross section is formed into a shape such as an I-beam. (in this lab, you will only do flat rolling)

Shape Rolling

Flat Rolling

Shape Rolling

Raw material and final product both in flat and shape rolling
Introduction to Rolling

After casting, ingots are rolled into one of three intermediate shapes called blooms, billets, and slabs:

1. Blooms have square cross section 6” x 6” or larger. They are rolled into structural shapes.

2. Billets have square cross section 1.5” x 1.5” or larger. They are rolled into bars and rods.

3. Slabs have rectangular cross section 10” x 1.5” or larger. They are rolled into plates, sheets and strips.
Introduction to Rolling

• As any other metal forming process, rolling can be performed hot (hot rolling) or cold (cold rolling).

• Most rolling is carried out by hot rolling, owing to the large amount of deformation required.

• Hot-rolled metal is generally free of residual stresses, and has isotropic properties. On the other hand, it does not have close dimensional tolerances, and the surface has a characteristic oxide scale. Moreover, cold rolled metals are stronger.

In this lab, you will only do cold rolling (at room temperature).
Flat rolling and its analysis

- In flat rolling, the work is squeezed between two rolls so that its thickness is reduced by an amount called the draft:

\[ d = t_o - t_f \]

where

- \( d \): draft
- \( t_o \): starting thickness
- \( t_f \): final thickness

- As a fraction of the starting thickness:

\[ \% \ reduction = \% \ r = \left( \frac{d}{t_o} \right) \times 100\% \]
Flat rolling and its analysis

- Rolling increases work width. This is called “spreading”.

- Spreading is expected because of the volume constancy in plastic deformation. Since the material is compressed in the thickness direction, both the length and width will increase provided that the material is not constrained in the width direction.

- Spreading is more pronounced with low width-to-thickness ratios and low coefficients of friction, since there is small resistance to flow in the width direction.
Flat rolling and its analysis

• The width-to-thickness ratio can be calculated as follows:

\[ \frac{w}{t} \text{ Ratio} = \frac{\text{initial width}}{\text{initial thickness}} \]

• After rolling, percentage spread can be calculated as follows:

\[ \% \text{ Spread} = \left( \frac{\text{Final width} - \text{initial width}}{\text{initial width}} \right) \times 100\% \]
Flat rolling and its analysis

• The work contacts the rolls along a contact arc. To calculate the arc length, you can use the following approximate formula:

\[ L = (R \times d)^{0.5} \]

Where

L: approximate contact length, R: roll radius, d: draft

(See the next figure)

• If the width-to-thickness ratio is large, then the spread will be negligible and a “plane-strain” condition may be assumed. Plane strain means that deformation occurs only in two directions (in a plane); the longitudinal (rolling) direction and the transverse direction.
This figure shows the contact length between the work and the rolls, the initial and final work velocities, in addition to the velocity of the rolls:
Flat rolling and its analysis

• The work enters the gap between the rolls at a velocity $v_o$ and exits at a velocity $v_f$. Because the volume flow rate is constant and the thickness is decreasing, $v_f$ should be larger than $v_o$.

• The roll surface velocity $v_r$ is larger than $v_o$ and smaller than $v_f$. This means that slipping occurs between the work and the rolls.

• Only at one point along the contact length, there is no slipping (relative motion) between the work and the roll. This point is called the “Neutral Point” or the “No Slip Point”.

Flat rolling and its analysis

The true strain experienced by the work in rolling is based on the stock thickness before and after rolling:

$$\varepsilon = \ln \left( \frac{t_0}{t_f} \right)$$

The average flow stress in flat rolling can be determined by:

$$Y_{avg,f} = \frac{K \varepsilon^n}{n + 1}$$

Where:
K: Strength coefficient
n: Strain hardening exponent
(see the tensile testing module for more information about the power law \( \sigma = K \varepsilon^n \))
Flat rolling and its analysis

• In this experiment, a sheet will be rolled on 4 stages (4 passes).
• In each pass, the average flow stress can be determined using the following formula:

\[
Y_{avg,i} = K \frac{\varepsilon_i^{n+1} - \varepsilon_{i-1}^{n+1}}{(\varepsilon_i - \varepsilon_{i-1})(n+1)}
\]

where

\(Y_{avg,i}\) : the average flow stress in the \(i^{th}\) pass
\(\varepsilon_{i-1}\) : the strain after the \((i-1)^{th}\) (before the \(i^{th}\) pass) = \(\ln \left(\frac{t_o}{t_{i-1}}\right)\)
\(\varepsilon_i\) : the strain after the \(i^{th}\) pass = \(\varepsilon = \ln \left(\frac{t_o}{t_i}\right)\)
\(K\) : Strength coefficient
\(n\) : Strain hardening exponent
To calculate the roll force required to maintain separation between the two rolls:

\[ F = 1.15 \times Y_{avg, i} \times L_i \times w_i \]

where:
- \( F \): roll force
- \( Y_{avg, i} \): the average flow stress in the \( i^{th} \) pass
- \( L_i \): the approximate contact length in the \( i^{th} \) pass
- \( w_i \): the width of the sheet in the \( i^{th} \) pass
The torque in rolling can be estimated by:

\[ T = 0.5 \times F \times L \]

Where:
T: Torque (lb.in or N.m)
F: Roll Force
L: Contact length

The Power required to drive the two rolls is calculated as follows:

\[ P = 2\pi \times N \times F \times L \]

Where:
P: Power (in J/s =Watt or in-lb/min)
N: Rolls rotational speed (RPM)
F: Roll Force
L: Contact length
Flat rolling and its analysis

From the previous equations we can conclude the following:

1. The contact length decreases by decreasing the roll radius.
2. The roll force depends on the contact length, and therefore, reducing the roll radius will reduce the roll force.
3. The torque and power depend on the roll force and contact length, and therefore, reducing the roll radius will reduce both the torque and power.
4. The power also depends on the rotational speed of the rolls, and therefore, reducing the rolls RPM will reduce the power.
Flat rolling and its analysis

- On the **entrance**-side of the no slip point, the roll is **faster** than the sheet and therefore the friction force is **in** the **rolling** direction.

- On the **exit**-side of the no slip point, the roll is **slower** than the sheet and therefore the friction force is **opposite** to the **rolling** direction.

- The compression force on the rolls multiplied by the friction coefficient equals to the friction force.

- Increasing the friction coefficient will shift the neutral point toward the entrance.
Flat rolling and its analysis

• In rolling, friction force is important because it is responsible for pulling the sheet between the rolls.

• Rolling may not be possible (the sheet will not be pulled) if the draft is large. The maximum draft for successful rolling is:

\[ d_{\text{max}} = \mu^2 R \]

Where:
- \( d_{\text{max}} \): maximum draft for successful rolling
- \( \mu \): coefficient of friction
- \( R \): roll radius

• As can be seen from the equation, if \( \mu \) is zero, then \( d_{\text{max}} \) is also zero (rolling is not possible)
Defects in rolling may be either surface or structural defects:

- **Surface defects** include *scale* and *roll marks*.
- **Structural defects** (see next figure) include:
  1. **Wavy edges:**
     
     Bending of the rolls causes the sheet to be thinner at the edges, which tend to elongate more. Since the edges are restricted by the material at the center, they tend to wrinkle and form wavy edges.
  2. **Center and edge cracks:** caused by low material ductility and barreling of the edges.
  3. **Alligatoring:** results from inhomogeneous deformation or defects in the original cast ingots.
- **Other defects** may include residual stresses (in some cases residual stresses are desirable).

Flat rolling defects

Structural defects in sheet rolling:

- Wavy Edges
- Center cracking
- Edge cracking
- Alligatating

Various rolling mill configurations are available (see next figure):

1. Two-high rolling mill: consists of two opposing rolls. These rolls may rotate only in one direction (nonreversing) or in two directions (reversing).

2. Three-high rolling mill: allows a series of reductions without the need to change the rotational direction of the rolls.

3. Four-high rolling mill:
   Using small rolls reduces power consumption but increases the roll deflection. In this configuration, two small rolls, called working rolls, are used to reduce the power and another two, called backing rolls, are used to provide support to the working rolls.

4. Cluster rolling mill: another configuration that allows smaller working rolls to be used.

5. Tandem rolling mill: series of rolling stands.
Rolling mills

Various configurations of rolling mills:

(a) Two-high
(b) Three-high
(c) Four-high
(d) Cluster
(e) tandem
Lab Objectives

This lab has the following objectives:

• Introduce basic rolling parameters and some of the fundamental principles in rolling.
• Calculate the roll forces required to reduce the thickness of a given aluminum strip.
• Verify plane strain assumptions used in rolling analyses.
• Identify where plane strain assumptions are not valid and to calculate the percentage spread in such cases.
• Evaluate the strain hardening phenomena in rolling processes.
• Identify some defects involved in rolling processes.
Equipment

• In this lab, you will use a scale-down model of an industrial rolling mill. The rolling mill has two rolls powered by an electric motor.

• The distance between the rolls, which is the roll gap, can be adjusted by rotating a pair of rotationally calibrated screws at the top of the roll stand (housing).

• To keep the roll gap constant, you should ensure that the two adjusting screws have been adjusted to the same calibration number. There is a mark on each roll housing used to align the calibration marks on the adjusting screws.
A picture of the scale-down rolling mill used in the lab:
Equipment

Adjusting screw

Calibration numbers
Procedure

Part I: Rolling

1- Obtain the material data (K, n) from your lab instructor and record it in your datasheet.
2- Record the following initial conditions of your sample strip in the table provided:
   a) Thickness
   b) Length
   c) Width
   d) Hardness (HRC); average of three measurement
3- Set the roll gap for the first pass (set the adjusting screw to 5)
4- Start the rolling mill
Procedure

Part I: Rolling (continued)

5- Feed the strip through the mill (make sure not to feed the strip at an angle into the rolls).

6- In the table provided, record the:
   a) Thickness
   b) Length
   c) Width
   d) Hardness (HRC); average of three measurement

7- Reduce the roll gap by one unit per pass and repeat steps 3-6 for the remaining four passes.
Part II: Estimating the coefficient of friction

1- With a new sample, record the initial thickness.
2- Measure the roll radius.
3- Set the roll gap to 1 on the adjusting screw.
4- Start the rolling mill.
5- Very gently attempt to feed the strip through the mill, but do not force the strip into the mill. Hold the strip as level as possible and let friction between the rolls and the strip pull it in (this must be the case to get accurate data regarding the friction force). Note: the strip will not be pulled in on this first attempt.
Part II: Estimating the coefficient of friction (Continued)

6- Open the roll gap by steps on one-half units on the roll set screw and repeat step 5 until the mill just pulls in the strip. The number on which the roll is set is not important and only the initial and final thickness of the specimen are needed.

7- Record the final thickness and complete the calculations with the formulas provided.
Procedure

Part III: Transverse strains in rolling (Spread)

In this section of the lab, we will use a strip of aluminum that has lower width to thickness ratio. This section highlights the fact that plane strain assumptions in rolling must be used carefully and only for particular cross-sections.

1- Record the specimen initial width and thickness.
2- The lab instructor will set the roll gap to 3
3- Roll the strip and then record the final width and thickness.

You will notice that there is a change in all dimensions.
A picture showing the strips to be used in the lab:

High w/t ratio

Low w/t ratio
Picture showing the sheet rolling process:

Plane strain condition expected

Spread expected
Summary-Rolling

This lab preparation material introduced:

• Basic principles of rolling
• Analysis for flat rolling operations
• Flat rolling defects
• Rolling defects
• Lab objectives, Equipment and procedures
• Pictures